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NIST-GCR-89-565

Upward Flame Spread on Vertical Walls

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April 1989

Issued June 1989

Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

Notice

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U.S. DEPARTMENT OF COMMERCE
Robert Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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UPWARD FLAME SPREAD ON VERTICAL WALLS

by

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FINAL REPORT

on Grant No. 60NANB4D0037

submitted to Center for Fire Research
National Institute of Standards and Technology
Gaithersburg, MD 20899

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ABSTRACT

Progress made on NIST Grant No. 60NANB4D0037 is reported here. Since the three previous annual reports describe the work conducted in the first three years, the scope of this report is limited to the past (and final) year of the grant, in which a study of upward flame spread on vertical walls was conducted. First, a detailed review of literature on upward flame spread is presented. A "complete procedure" for predicting upward flame spread on practical materials, which can be used in a global fire hazard assessment model, is then described. Experimental results on upward flame spread on various materials are obtained and the validity of the model is established.

TABLE OF CONTENTS

	Page
ABSTRACT	i
NOMENCLATURE	ii
INTRODUCTION	1
Part A: Upward Flame Spread: A Review	7
Part B: Mathematical Model	22
Part C: Measurement of Local Mass Loss Rate	27
Part D: Upward Flame Spread: Experimental Setup	30
Part E: Results and Discussion	32
Part F: Conclusions	38
REFERENCES	39
FIGURES	44
ACKNOWLEDGEMENTS	61

NOMENCLATURE

a : A constant in Eq. 4

a_o, a_1, etc.: Constants in Eq. 20

b_o, b_1, etc.: Constants in Eq. 28

c : Heat capacity

F_e : Excess fuel fraction

h : Heat transfer coefficient for heat loss

h_c : Heat of combustion

k : Thermal conductivity

K, n : Constants in the flame height correlation

m'' : Combustible mass per unit area in the fuel wall

$\dot{m}''$: Local mass loss rate per unit area as a function of time

q_w or $\dot{q}''_w$: Total heat flux to unburnt fuel

$\dot{q}''_o$: Heat flux from flame to surface at the pyrolysis front

$\dot{Q}'$: Energy release rate per unit width

$\dot{Q}''_o$: Igniter strength

t : Time

t_b : Burnout time

t_f : Inert heating time constant

T : Temperature

T_a or T_∞: Ambient temperature

T_{ig} : Surface or ignition temperature

V_p : Upward flame spread velocity

V_{po} : Initial upward flame spread velocity

$\bar{V}$: Dimensionless velocity

x_b : Burnout edge

x_f : Flame front

x_{fo} : Initial flame height

x_p : Pyrolysis front

x_{po} : Initial pyrolysis height

δ : A characteristic length

λ : Dimensionless time

ρ : Density

INTRODUCTION

This is the final technical report on NBS Grant No. 60NANB4D0037, which expired on February14, 1989. The investigation involved problems related to vertical wall fires. In the first year of the grant, a comprehensive mathematical model for a laminar wall fire in a stratified ambient atmosphere was formulated and numerical solutions were obtained. In the second year, a laboratory test program was initiated in which an experimental apparatus was designed and built to simulate a wall burning in a thermally stratified, quiescent atmosphere having a nonuniform ambient oxygen mass fraction variation in the vertical direction. Also, a model for a laminar-transitional-turbulent, natural convection flow in a stratified atmosphere, was formulated and solved. In the third year, measurements on a small-scale wall fire in various types of stratified ambient atmosphere were completed and comparisons of the data were made with numerical predictions from the wall fire model developed earlier. Also, experiments in a salt-water model of buoyant plume in a stratified atmosphere were designed and completed. In the fourth and final year of the grant period, a model for upward flame spread on a vertical wall was developed, small and large scale experiments on upward flame spread were designed and setup, and flame spread data were obtained for various materials.

The progress made and work accomplished in the first three years of the grant period are described in detail in several quarterly and three annual reports published by NIST. The annual reports are listed below:

1. "A Model for Vertical Wall Fire in a Stratified Atmosphere", by A.K. Kulkarni and J.J. Hwang, Annual Report on Grant No.

60NANB4D0037 for the period 8/15/84 to 8/14/85. Also issued as NBS Report No. NBS-GCR-86-510, (1986).

2. "Vertical Wall Fire in a Stratified Atmosphere," by A.K. Kulkarni, J.J. Hwang and S.L. Chou, Annual Report on Grant No. 60NANB4D0037 for the period 8/15/85 to 8/14/86. Also issued as NBS Report No. NBS-GCR-87-525, 52 pages (1987).
3. "Fire and Fire-Induced Flows in a Stratified Atmosphere," by A.K. Kulkarni, J.J. Hwang and F. Murphy, Annual Report on Grant No. GONANB4D0037 for the period 8/15/86 to 8/14/87. Also issued as NBS Report No. NBS-GCR-88-548, 49 pages (1988).

Since the work conducted in the first three years of the grant period is described in the above-mentioned reports, this report primarily presents the progress on the work conducted in the past year of the grant period.

During a large part of the fourth year of the grant period, the P.I. was on a sabbatical leave at NIST, therefore, the research work was planned such that it would be conducted at NIST. In this period, a study of upward flame spread on vertical wall fires was undertaken. The overall objectives were (i) to develop a mathematical model to predict upward flame with properly identified "fire properties" of materials as input to the model, and (ii) to conduct appropriate experiments to test the validity of the model.

Major achievements made during the past year are summarized below:

1. A thorough review of upward flame spread models and experiments was made.

2. A mathematical model was developed for upward flame spread on vertical walls. Also, relevant "fire properties", which are needed as input to the model, were identified.
3. A mass loss rate measurement apparatus was designed, fabricated, and tested. It gives the local mass loss rate of a given fuel as a function of time for use in the mathematical model for the prediction of upward flame spread.
4. An apparatus for gathering flame spread rate data on various wall-like materials was designed and constructed.
5. Upward flame spread experiments were conducted on samples of several materials of 30 cm x 120 cm size and 45 cm x 2.1 m size.
6. Predictions for various materials were made and compared with data.

The progress made in the past year (which is summarized above) is presented in detail in several parts of this report.

Lists of publications and theses, based on the work conducted during the four years of this grant, are given below:

Publications:

Kulkarni, A.K., J.J. Hwang. A Model for a Burning Vertical Wall in the Stratified Atmosphere of a Compartment Fire. Proceedings of the 1985 Fall Technical Meeting, Eastern Section of the Combustion Institute, November 1985.

Kulkarni, A.K., J.J. Hwang. Free Convection Vertical Wall Fire in Various Types of Stratified Ambient Atmosphere. AIAA 24th Aerospace Sciences Meeting, Paper No. AIAA-86-0577, January 1986.

Kulkarni, A.K., J.J. Hwang. An Experimental Study of Vertical Wall Fire in a Stratified Atmosphere. Proceedings of the Eastern Section Combustion Institute Meeting, December 1986.

Kulkarni, A.K., and J.J. Hwang. Vertical Wall Fire in a Strtified Ambient Atmosphere. Proceedings of the Twenty-First International Symposium on Combustion, The Combustion Institute, PA, p. 45, 1986.

Kulkarni, A.K., H.R. Jacobs, and J.J. Hwang. Natural Convection Over an Isothermal Vertical Surface Immersed in a Thermally Stratified Fluid. Interntional Journal of Heat and Mass Transfer, 30, pp. 691-698, 1987.

Kulkarni, A.K. Radiative Heat Transfer from Wall Fires, Radiation, Phase Change Heat Transfer and Thermal Systems, proceedings of the 1987 ASME Winter Annual Meeting, pp. 9-16, 1987.

Heat and Mass Transfer in Fire, Ed., A.K. Kulkarni and Y. Jaluria, proceedings of the session in 1987 National Heat Transfer Conference, Pub. American Society of Mechanical Engineers, 1987.

Kulkarni, A.K., F. Murphy. Buoyant Jet in a Two-Layer Stratified Medium. Symposium on Natural Circulation, 1987 ASME Winter Annual Meeting, p. 313, 1987.

Kulkarni, A.K. and Kim, C.I. Heat Loss to the Interior of a Free Burning Vertical PMMA Slab and Its Influence on Heat of Pyrolysis, presented at the Fall Technical Meeting of the Eastern Section of the Combustion Institute, 1988. Also accepted for presentation at the National Heat Transfer Conference, 1989.

Kulkarni, A.K. and Fisher, S. A Model for Upward Flame Spread on Vertical Wall, presented at the 1988 Fall Technical Meeting of the Eastern Section of The Combustion Institute, 1988.

Kulkarni, A.K., S.L. Chou. Turbulent Natural Convection Flow on a Heated Vertical Wall Immersed in a Stratified Atmosphere. American Nuclear Society Proceedings of the 1987 National Heat Transfer Conference, pp. 216-223, 1987. Also, Journal of Heat Transfer (in press).

Hwang, J.J. and A.K. Kulkarni. An Experimental Study of Vertical Wall Fire in a Stratified Atmosphere. International Journal of Experimental Heat Transfer, Thermodynamics and Fluid Mechanics (in press).

Theses

Chou, S.L., Turbulent Natural Convection over a Vertical Surface Immersed in a Stratified Atmosphere, M.S. paper, Department of Mechanical Engineering, The Pennsylvania State University, January 1987.

Murphy, F., Salt Water Modeling of a Buoyant Jet Plume in a Two-layer Stratified Environment, M.S. paper, Department of Mechanical Engineering, The Pennsylvania State University, January 1987.

Hwang, J.J., Vertical Wall Fire in a Stratified Atmosphere, Ph.D. Dissertion, Department of Mechanical Engineering, The Pennsylvania State University, December 1987.

Kim, C.I., Ph.D. Student, Upward Spread in Wall Fires, in progress.

PART A

UPWARD FLAME SPREAD: A REVIEW

When a material burns in a vertical configuration, upward flame spread becomes highly significant because it is most rapid in this direction compared to the lateral and downward spread in wall fires. Upward spread provides an important vehicle for fire growth, after its inception in a remote location to other parts of a compartment. It is, therefore, imperative that in evaluating fire hazard in a building, a zone model should account adequately for upward flame spread rates for a given set of atmospheric conditions, wall material, and geometry. Another reason for understanding the upward flame spread phenomenon is that it can suggest a method for identifying effective material properties that can quantitatively assess the flammability of materials in vertical orientation, allowing a relative ranking of different materials.

It is known that the flame spread process depends on how fast the unburnt fuel ahead of the pyrolysis front can be heated to a critical temperature (or a range of temperatures) that causes significant pyrolysis. Heating of the unburnt fuel is caused by energy transfer by convection and radiation from flames and plumes, as well as via conduction through the condensed phase. Compared to lateral and downward flame spread, the upward spread problem is particularly difficult because of (a) the generally transient nature of the spread rate and (b) the strong and dominating effect of energy feedback from flames to the fuel which intricately depends on several other characteristics of the fuel. During upward spread, flames from the pyrolyzing area cover the unburnt fuel which is eventually ignited, and the size of the newly created flames in turn depends on the magnitude of the burning rate. Thus, the most

challenging and fundamental aspect of an upward spread model is the determination of the net forward heat flux to the unburnt fuel as a function of time and position, $\dot{q}''_f(x,t)$, which may be obtained analytically, or empirically from experiments, or by a combination of the two approaches. As pointed out below in the Background section, a large number of models proposed in the literature so far differ mainly in how to model $\dot{q}''_f(x,t)$ appropriately, which then use one of the several analytical techniques (ranging from simple algebraic to extensively numerical) to predict the upward spread rate.

Upward Flame Spread Models

The earliest attempts at modeling upward flame spread were made by Thomas and others [Thomas and Lawson (1957), Thomas and Webster (1960), Thomas (1975)] who had fully recognized the importance of the forward heat flux to, and the loss of heat from, the unburnt fuel ahead of the pyrolysis front. Thomas wrote, "If the heat flux from the burning zone, either from the fuel bed or the gas phase outside, is assumed to have a certain value and is treated as an independent variable and if the propagation is regarded as being controlled by the attainment of a certain surface temperature at which hot flammable gases are released rapidly so that there is no restriction on the rate of propagation by lack of fuel in the gas phase or by slow reaction rates, a simple model of spread may be written down from a heat balance of the unburnt fuel ahead of the fire." Thomas and others (1960, 1975) proposed a steady state upward flame spread (V_p) equation,

$$V_p = \frac{4\delta}{\pi k \rho c}\left[\frac{\dot{q}''_o - h(T_{ig} - T_\infty)}{T_{ig} - T_\infty}\right]^2 \qquad (1)$$

where δ is a characteristic length signifying the heat flux ahead of the pyrolysis front, $\dot{q}''_o$ is the heat flux from flame to surface at the pyrolysis front, h is the heat transfer coefficient for heat loss, T_{ig} is ignition temperature, T_∞ is ambient temperature, and k, ρ, c are thermal conductivity, density and heat capacity of the solid fuel. They also emphasized the greater importance of δ in the upward flame spread, compared to horizontal flame spread in which conduction through the condensed phase is of prime importance [deRis, 1969].

The early work on upward flame spread was confined mainly to thermally thin solids because of interest in the burning of paper and textiles. Although burning walls in practical fires typically behave like thermally thick solids, many of the fundamental mechanisms of upward spread are common between the thermally thick and the thermally thin solids. Therefore, relevant models for thin fuels are also reviewed here.

The first detailed model of upward flame spread was proposed by Markstein and deRis (1972) for burning of a fabric. They assumed that the forward heat transfer (from flame to unburnt fabric ahead of the pyrolysis front) was constant up to the flame tip and then dropped to zero. They modeled the forward heat flux, $\dot{q}''_f$, as

$$\dot{q}''_f[x_f(t) - x_p(t)] = K[x_p(t) - x_b(t)]^n \qquad (2)$$

where $x_f(t)$, $x_p(t)$ and $x_b(t)$ are time dependent flame front, pyrolysis front and burnout edge, respectively. The constants K and n were obtained from experiments on flat, vertical gas burners simulating various fabric pyrolysis lengths. They also made use of burnout time, t_b (which is the time period required to completely burn the fuel at a given location starting at the instant of ignition) and preheating time, t_f (which is the time required to preheat the thin solid from the initial temperature to the

pyrolysis temperature). Based on these parameters they obtained a first order differential equation which was then solved to obtain the upward flame spread rate, defined as the propagation rate of the pyrolysis front. In a simplified form they found $V_p \alpha(x_p)^m$, where m was a constant. Their predictions agreed reasonably well with experiments.

As we shall see later the concepts of using preheat time, burnout time, forward heat flux based on the flame height, and correlation of flame height to pyrolysis height as used by Markstein and deRis (1972) proved to be very important and these were used with some variation of definitions in several subsequent models.

Orloff *et al*, (1975) proposed a model where they assumed the flame height, x_f, to be $x_f(t) = Kx_p^n = x_p(t+t_f)$, and with the burnout front fixed in the original position (thick fuel slabs). The forward heat flux, $\dot{q}''_w$, was assumed to be constant up to x_f and zero thereafter. The pyrolysis front, therefore, moved in a leapfrogging manner, i.e., it moved a distance of $(x_f - x_p)$ after every period t_f, which was then made smooth through an approximation. The value of $\dot{q}''_w$ was obtained from steady state wall burning experiments. They found that the fire spread rate increased exponentially with time.

Sibulkin and Kim (1977) assumed the forward heat flux to be exponentially decreasing with distance from the pyrolysis front, with a length scale of δ which was correlated to experimentally measured heat flux and other parameters. For fuels that were not thermally thick, δ increased with the thickness of the fuel slab. For semi-infinite (thermally thick) fuels the process was found to be unsteady; however, an approximate quasi-steady solution for the flame spread velocity was presented in terms of δ, $\dot{q}''_w$ and other properties as

$$V_p = \frac{(\dot{q}''_w)^2 \delta}{k\rho c\,(T_{ig} - T_s)^2} \qquad (3)$$

where T_s is the initial surface temperature of the fuel. They expressed $\dot{q}''_w$ and δ in terms of x_p and other properties for laminar and turbulent cases. They also assumed the burnout edge, x_b, to be fixed.

Fernandez-Pello (1978) presented a comprehensive mathematical model for nonradiating, small (laminar) fires with self-similar profiles of velocity and temperature in the pyrolysis and downstream regions, obtained from numerical solution of a set of parabolic governing equations. Based on the solution of these equations, he obtained predictions for acceleratory vertical flame spread which showed that

$$V_p \alpha (x_p - x_b)^{3/4} \alpha t^{3/2}$$

This model was later modified to account for the effects of external radiation (Fernandez Pello, 1977; Note: this paper appeared in literature before the previously mentioned paper). The external radiation substantially affected the flame spread rate, primarily via the elevated initial surface temperature, T_s. Subsequently, Fernandez Pello (1979) developed another comprehensive model without buoyancy but with externally imposed flow velocity (forced flow). And later, a model was presented for mixed convection (forced and free) of which upward flame spread was a special case (Fernandez-Pello and Mao, 1981).

The theoretical predictions of Fernandez-Pello and co-workers were found to be in qualitative agreement with experimental results. Their models are perhaps the most comprehensive and complete mathematical models of upward flame spread within the framework of certain assumptions. However, from the point of view of applying these models to practical situations, there are following major restrictions: (a) the fire

and induced flow field were assumed to be laminar and non-radiating which are far from most real situations; (b) the burning rate of fuel ($\dot{m}''$) was assumed to be constant, which is not true for most of the practical materials in use (especially for charring fuels like wood, which exhibit an initial peak in mass loss rate as a function of time); (c) the prediction of the flame propagation velocity is numerically intensive, requiring solution of a set of partial differential equations which puts severe restrictions on the use of this model in a global, zone model for predicting fire hazard in a multi-room building.

An upward flame spread model using integral analysis was first presented by Annamalai and Sibulkin (1979 a, 1979 b) for laminar flames who derived expressions for the excess fuel fraction F_e (unburnt gasified fuel available at the pyrolysis front) and forward heat flux, $\dot{q}''_f$, in terms of the Spalding B number and a parameter r (B and r in turn are expressed in other fuel properties). Based on the calculation of F_e, they determined the ratio of flame height to pyrolysis height (x_f/x_p) in terms of B and r. Finally, they found a complex but closed-form algebraic expression for the upward spread rate as a function of B, r, other fuel properties, and the initial pyrolysis height, x_{po}. The theory overpredicted the experimentally measured flame rates of Fernandez-Pello (1977), Orloff *et al.*, (1975) and Hansen and Sibulkin (1974) by a factor of two; the discrepancy was attributed to the net forward heat flux estimation errors (such as the neglect of surface reradiation). Thus, the quasi-steady model of Annamalai and Sibulkin (1979 a, 1979 b) for upward flame spread was partially successful in predicting upward flame spread rates using a closed expression and without having to solve the problem with extensive numerical solutions of partial differential equations like those of

Fernandez-Pello (1977). However, from a practical point of view, the applicability of the model was once again restricted due to the assumption of laminar flow, inability to handle realistic fuels like charring woods or those having time-dependent burning rates, and difficulties in accurately modeling the forward heat transfer.

One of the first upward flame spread models to take into account turbulence, radiation, and charring was proposed by Fernandez-Pello and Quintiere (1982). They obtained the following expression for the upward spread velocity:

$$V_p = \frac{4a\delta(\dot{q}''_f)^2}{(h(T_{ig} - T_i) - \dot{q}''_o)^2} \qquad (4)$$

The forward heat transfer, $\dot{q}''_f$, was based on theoretically predicted convective and radiative heat fluxes and empirical correlations (of Ahmad and Faeth, 1978 and Kinoshita and Pagni, 1981) and the pyrolysis height, x_p. The flame height was calculated from the air entrainment required to burn excess fuel in which the effects of turbulence and the effective heat of pyrolysis were included with consideration to turbulence and radiation. In the above expression (eq. 4) the term "a" is a parameter representing an effective convective heat transfer coefficient which includes linearized surface reradiation, thermal conductivity, and entrainment constant. This model took into account most of the important aspects of the upward spread problem in a simple manner (for example, charring was treated as a constant factor reducing the heat of pyrolysis and the convective portion of $\dot{q}''_f$ was assumed to be proportional to x^n). Their final expression for V_p contained x_p, which was in turn possible to obtain from the solution of a first order differential equation.

Delichatsios (1984) discussed a limiting condition on upward flame spread, namely, the condition for which the flame propagation ceases due to heat loss to the interior of a charring fuel. In this semiempirical model he considered heat transfer through the char layer via radiation and then to the interior by conduction, derived a time-dependent mass loss rate based on the pyrolysis thickness, used an available correlation for the flame height in order to obtain the variation of the forward heat transfer, and then obtained characteristic ignition and decay times to determine if flame spread was sustained or not. However, he did not attempt to predict the flame spread rate *per se* in this model.

Quintiere (1985a) proposed an upward flow model (which was similar in many respects to the opposed flow and lateral spread models given in Quintiere, 1981) that included linearized surface reradiation heat loss by the as yet unpyrolyzed fuel ahead of the pyrolysis front, as well as the (decreasing) heat gain by the surface due to the plume above the flame height x_f. He expressed V_p as a function of x_p for a forward heat flux which was modeled as

$$\dot{q}''_w(x) = \dot{q}''_o = \text{constant for } x_p < x < x_o$$
$$= \dot{q}''_o \left(\frac{x}{x_o}\right)^{-2} \text{ for } x > x_o$$

where $x_o = 0.44 x_f$

The above distribution of forward heat flux, with the assumption of no heat loss by surface reradiation, simplified to a complex but closed form analytical solution for V_p. Although detailed results were not presented and compared with data, this is one of the few models that took into account the effect of overfire plume. Hasemi (1986) expressed the flame

spread rate, based on the conduction heat transfer analysis for a spatially varying heat flux (Luikor, 1968), as

$$V_p = \left[\int_0^{x_p} (\dot{q}''_w(x)/\sqrt{x - x_p})dx\right]^2 / \pi k\rho c(T_{ig} - T_s)^2 \qquad (5)$$

and then used an empirical expression for $\dot{q}''_w(x)$ based on experimental data obtained from gas line burners. The use of $\dot{q}''_w(x)$ data in general limited the applicability of the model because any specific mass loss characteristics $(\dot{m}''(t))$ were not taken into account. Also, the transient nature of the upward flame spread was completely ignored, and x_p was treated as an independent variable in the prediction of V_p.

Quintiere, *et al.*, (1986) proposed an upward spread model assuming a quasi-steady flame spread rate,

$$V_p = [x_f(t) - x_p(t)]/t_f$$

They obtained the flame height, x_f, from integral analysis of turbulent wall flames in terms of the physical properties and energy release rate per unit width with the assumption that $\dot{m}''$ is constant. The characteristic time, t_f, was expressed using the theory of conduction in a semi-infinite solid with a constant heat flux. Based on an integral analysis $\dot{q}''_w(x)$ was initially expressed as $(x/x_f)^{-1/2}$; however, their experimental data showed that $\dot{q}''_w(x)$ was approximately constant. Therefore, $\dot{q}''_w(x)$ was assumed to be a known constant up to the flame height. The pyrolysis height, $x_p(t)$, was in turn correlated with the flame height (x_f) and the burnout height (x_b), and expressed as an exponential function of time with the burnout time t_b as one of the key parameters. Although an explicit expression for V_p was not presented, several important parameters controlling the upward flame spread (such as T_{ig}, t_f, t_b, $k\rho c$, forward heat flux correlation parameters, flame length correlation

parameters, and pilot flame parameters) were identified. Some of the parameters were tabulated and experimental techniques to measure them were discussed (Quintiere *et al.*, 1983, Harkleroad *et al.*, 1983).

Saito *et al.*, (1986) further modified the model of Quintiere *et al.*, (1986) to include a nonuniform local burning rate $\dot{m}''(x)$. By converting the height dependence of $\dot{m}''(x)$ into time-dependence via the upward spread velocity, they obtained a retarded integral equation (Volterra type) for the spread rate, V_p, which was analyzed further using approximate analytical methods for two specific cases, $\dot{m}''(t)$ = constant and $\dot{m}''(t) \sim (t - t_b)^{-1/2}$. Although no explicit results of V_p were presented, its asymptotic behavior (short time and long time) was discussed for the two cases.

Recently, Mitler (1986,1988), Delichatsios (1988), and others discussed various algorithms for the upward flame spread problem. Mitler (1988) presented a numerical method which is based on the solution of the unsteady heat conduction equation in a semiinfinite slab with boundary conditions which include convective and radiative heat transfer. Delichatsios (1988) presented a retarded integral equation for heat conduction in a semiinfinite solid. However, in both cases, the forward heat transfer, $\dot{q}''_f(x,t)$, must be known or prescribed.

Other Related Models

The concurrent, forced flow flame spread problem has several similarities with the natural convection upward spread problem, the most important being that the forward heat transfer is primarily from the flames, and not by conduction through the condensed phase. The difference between the two problems is that the concurrent forced flow

flame spread is driven by the external flow field and the gravitational effects are negligible. Fernandez-Pello (1979) solved the governing equations numerically to obtain the forward heat transfer, and subsequently, the flame spread rate. Carrier *et al.*, (1983) did extensive mathematical analysis of the problem with consideration to radiation and char formation, and obtained three coupled, non-linear, Volterra equations. They obtained temperature, flow field, and mass loss results for several simplified cases. Wichman and Baum (1988) have applied an integral approach to this problem. Models attempting to gain insight into the ASTM-84 tunnel test method, which examines wind-aided flame spread, have been presented by deRis (1969), Frey and Tien (1977), Quintiere (1981), and Quintiere (1985b). These models are applicable to upward flame spread only if there is an upward draft of air on a burning vertical wall, where the draft is so strong that it overwhelms the effects of buoyancy. However, most practical wall fires are dominated by natural convection, and therefore forced flow models will not be considered further.

Experimental Studies of Upward Spread

Experimental studies of upward flame spread are considerably few compared to modeling efforts. Earlier studies were conducted on textiles (Lawson *et al.*, 1955; Markstein and deRis, 1972) where they measured rates of upward flame spread on small scale samples of various fabrics. However, materials involved in wall fire situations are typically thermally thick; therefore only those studies will be considered here.

The first experimental study on upward flame spread on thermally thick fuels was reported by Hansen and Sibulkin (1974). They used

PMMA slabs for fuel and a point source of ignition, and studied the pyrolysis front contours and mass loss rate as a function of time for laminar fires. The first large scale, turbulent upward flame spread study was conducted by Orloff *et al.*, (1975) on 1.57m high PMMA slabs. The upward spread velocity was observed to increase exponentially with time, and almost linearly with distance. Fernandez-Pello (1977) studied laminar and upward flame spread over PMMA slabs under external radition conditions and found V_p increasing with time (accelerated flame spread throughout). Annamalai and Sibulkin (1978) conducted small scale experiments on eighteen different plastic and foam materials to determine if upward flame spread was possible, and if so how fast it was, under various levels of external radiation fluxes. Recenlty, Saito *et al.*, (1986, 1987) did upward spread tests on PMMA and wood slabs. They found that a critical (minimum) external radiation flux was needed for piloted ignition of wood (confirming a well known result) and that the flame spread ceased after a certain distance. For PMMA the spread was acceleratory once the external minimum flux was exceeded. However, their measurements were too limited in number for definitive, quantitative conclusions.

Forward Heat Flux

It must be noted that, in none of the above experiments was the transient heat flux ahead of the flame measured. Also none of the experiments conducted a systematic study involving movement of the burnout edge, x_b. Although $\dot{q}''_{-}(x,t)$ was not measured in the above experiments, several studies have reported measurement of the forward heat flux with a stationary pyrolysis front. Among them are Ahmad and

Faeth (1978, 1979) who presented data for burning of wicks soaked with several liquid fuels and correlated the data as a power of (x/x_p); Hasemi (1984) and Kulkarni (1987) who correlated data for linear gas burners; and Quintiere *et al.*, (1986) who reported data for burning of vertical slabs of six solid wall materials. Recently, Harkleroad and Tu (1988) have measured forward heat flux for fully burning vertical slabs of several different materials, with a simultaneous measurement of the time-dependent mass loss rate, $\dot{m}(t)$. The unsteadiness in $\dot{q}''_w(x,t)$ in their experiments was caused by the transient burning rate of materials such as particle board and PMMA, rather than by the flame spreading process.

Several analytical or numerical studies have attempted to model the forward heat transfer from basic principles; among them are detailed numerical models of Ahmad and Faeth (1978), Fernandez-Pello (1978) and Chen and Tien (1983); integral models of Ahmad and Faeth (1979), Annamalai and Sibulkin (1979a), and Quintiere *et al.*, (1986); and semiempirical models of Delichatsios (1984) and Quintiere (1985b) which are based on fundamental correlations of laminar and turbulent heat transfer and other theoretical considerations.

A number of articles have discussed in-depth, the subject of upward flame spread as a part of the overall flame spread process or in context to certain specific aspects of upward spread, as given in Thomas (1975), Williams (1976), Glassman (1981), Fernandez-Pello and Hirano (1983), Fernandez-Pello (1984) and Quintiere (1988).

Conclusions from the Past Work

Based on a review of the past literature on upward flame spread the following observations can be made:

1. The forward heat flux, $\dot{q}''_{w}$, is among the most important quantities which control the upward flame spread in wall fires and, therefore, all the models attempting to predict the upward spread rate must adequately account for $\dot{q}''_{w}$. Yet, none of the experimental investigations have tried to measure $\dot{q}''_{w}$ as a function of the distance and time in an upward spreading situation. Some data on $\dot{q}''_{w}(x)$ are available for actual wall materials; however, most of the measurements are for simulated wall fires such as gas line burners or liquid-fuel-soaked wicks.

2. Very little data are available on large scale (turbulent) wall fire upward flame spread rates. Thus, the development and verification of upward flame spread models is severely limited due to (i) the lack of well-characterized input data for $\dot{q}''_{w}(x,t)$ and (ii) absence of flame spread velocity data on most materials.

3. One of the important properties in upward spread is the burnout time, t_b, which dictates the size of the fire after the initial developing period. While many models have accounted for t_b, none of the experiments have systematically dealt with this parameter.

4. The importance of the time-dependent local mass loss rate, $\dot{m}''$, especially for charring materials, must be recognized and carefully incorporated into models. The unsteady burning rate affects the flame length and subsequently the heat flux, $\dot{q}''_w(x,t)$, and therefore it is fundamental to the behavior of the upward spreading fires. With the exception of one model, all of the current studies have ignored the transient nature of $\dot{m}''(t)$.

5. Many of the models have ignored surface heat loss by radiation for $x>x_p$ and heat gain of material due to plume gases for $x>x_f$. These terms have opposing effects on the upward spread rate, but they may be important, depending on specific conditions. This aspect needs to be explored further.

6. The finite difference numerical schemes such as the boundary layer flow models of predicting upward spread can be too extensive to be a part of a multi-room fire hazard prediction/assessment model. On the other hand, the simpler models have had to sacrifice important features for simplicity. A model is needed which is not numerically intensive, yet comprehensive enough to adequately account for various physical phenomena controlling the upward spread.

PART B

MATHEMATICAL MODEL

(Co-author: Dr. S. J. Fischer, NIST)

Concepts introduced in the upward flame spread models of Saito *et al.*, (1986) and Quintiere *et al.*, (1986) have been developed further to formulate a model that accepts certain measureable "fire properties" obtained from small scale experiments in order to predict the upward propagation of fire on a vertical wall made of a combustible material. The present formulation differs from the previous models in primarily two respects, (a) the present model accepts an arbitrarily specified local mass loss rate as a function of time, unlike the previous models which assume $\dot{m}''(t)$ to be either a square-wave or an exponentially decaying function, and (b) the present model allows as input a flame height correlation in the form of $x_f = \dot{Q}'^n$ (where x_f is flame tip height, $\dot{Q}'$ is energy release rate per unit length, and K and n are constants), unlike previous models which assumed n = 1 and simplified the analysis considerably.

The mathematical development of the model is given below. The nomenclature can be found in the beginning of the report. Figure 1 shows a schematic of the physical model of the upward flame spread process.

The upward flame propagation velocity is expressed here as a rate of increase of the pyrolysis front,

$$V_p = \frac{dx_p}{dt} \quad , \tag{6}$$

which can also be expressed approximately, for a quasi-steady flame process as,

$$V_p = \frac{x_f - x_p}{t_f} \quad , \tag{7}$$

where,

$$t_f = \frac{\pi k \rho c}{4}\left[\frac{T_{ig} - T_\infty}{q_w}\right]^2 . \tag{8}$$

The pyrolysis front can be written as,

$$x_p(t) = x_{po} + \int_0^t V_p(t')dt' \tag{9}$$

The flame height correlation is given by,

$$x_f(t) - x_b(t) = K\left[\dot{Q}_o + h_c \int_{x_b}^{x_f} \dot{m}''dx\right]^n , \tag{10}$$

and the burnout time is defined as,

$$\int_0^{t_b} \dot{m}''(t')dt' = m'' . \tag{11}$$

Two regimes of the time domain are considered separately, (a) $t < t_b$, during which the bottom edge is still burning and the igniter is on, and (b) $t > t_b$, during which the burnout front is above the igniter flame height. It is assumed here that the flame heat feedback is a prescribed constant up to the flame tip height and zero above the flame tip height, i.e., .

$$\dot{q}_w''(x) = \dot{q}_{w,o}'' = \text{constant}, \quad x_p < x < x_f$$
$$= o, \quad x > x_f \tag{12}$$

For $t < t_b$:

$$\int_{x_b}^{x_p} \dot{m}''\,dx = \int_0^{x_p} m''dx = \int_0^{x_{po}} \dot{m}''dx + \int_{x_{po}}^{x_p} \dot{m}''dx$$
$$= \dot{m}''(t)x_{po} + \int_0^t \dot{m}''(t - t')V_p(t')dt' \tag{13}$$

From Eqs. 6, 7 and 13, it can be shown that,

$$V_p(t) = \frac{1}{t_f}\left[K\left\{\dot{Q}_o + h_c\dot{m}''(t)x_{po} + h_{c_o}\int^t \dot{m}''(t-t')V_p(t')dt'\right\}^n - \left\{x_{po} + \int_o^t V_p(t')dt'\right\}\right] \tag{14}$$

for $t > t_b$:

$$\int_{x_b}^{x} \dot{m}''(t)dt = \int_{t-t_b}^{t} \dot{m}''(t-t')V_p(t')dt' \tag{15}$$

At $t > t_b$, the burnout front is advanced ahead of x_{po}. Assuming that the igniter is ineffective (or shutoff) at this time, $\dot{Q}'(t) = 0$,

$$V_p(t) = \frac{1}{t_f}\left[K\left\{h_{c\,(t-t_b)}\int^t \dot{m}''(t-t')V_p(t')dt'\right\}^n - {}_{(t-t_b)}\int^t V_p(t')dt'\right] \tag{16}$$

The above equations are made dimensionless using the following variables:

$$\lambda = t/t_f \quad ; \lambda' = t'/t_f \tag{17}$$

$$\bar{V}(\lambda) = \frac{V_p(t)}{V_{po}} \tag{18}$$

$$V_{po} = \frac{x_{f_o} - x_{po}}{t_f} \tag{19}$$

The local mass loss rate is expressed as

$$\dot{m}''(\lambda) = a_4\lambda^4 + a_3\lambda^3 + a_2\lambda^2 + a_1\lambda + a_o \tag{20}$$

The following additional variables are defined to aid in the solution of Eq. (14) and Eq. (16),

$$\frac{dE_1(\lambda)}{d\lambda} = \bar{V}(\lambda) \tag{21}$$

$$\frac{dE_2(\lambda)}{d\lambda} = E_1(\lambda) \tag{22}$$

$$\frac{dE_3(\lambda)}{d\lambda} = E_2(\lambda) \tag{23}$$

$$\frac{dE_4(\lambda)}{d\lambda} = E_3(\lambda) \tag{24}$$

$$\frac{dE_5(\lambda)}{d\lambda} = E_4(\lambda) \tag{25}$$

with these definitions, Eq. (14) becomes, for $t < t_b$,

$$\bar{V}(\lambda) = 1 + \frac{K}{x_{fo} - x_{po}} \left[\{ \dot{Q}_o + h_c x_{po} \dot{m}'' + h_c (x_{fo} - x_{po}) [a_o E_1(\lambda) + a_1 E_2(\lambda) + 2a_2 E_3(\lambda) + 6a_3 E_4(\lambda) + 24 a_4 E_5(\lambda)] \}^n - (\dot{Q} + h_c x_{po} a_o)^n \right] - E_1(\lambda) \tag{26}$$

and Eq. (16) becomes,

for $t > t_b$

$$\bar{V}(\lambda) = \frac{K}{x_{fo} - x_{po}} \{ h_c (x_{fo} - x_{po}) [(a_o E_1 + a_1 E_2 + 2a_2 E_3 + 6a_3 E_4 + 24 a_4 E_5) - (4a_4 \lambda_b^3 + 3a_3 \lambda_b^2 + 2a_2 \lambda_b + a_1) E_2(\lambda - \lambda_b) - (12 a_4 \lambda_b^2 + 6a_3 \lambda_b + 2a_2) E_3(\lambda - \lambda_b) - (24 a_4 \lambda_b + 6a_3) - 24 a_4 E_5(\lambda - \lambda_b)] \}^n - E_1(\lambda) + E_1(\lambda - \lambda_b) \tag{27}$$

The upward propagation velocity of the pyrolysis front, $V_p(t)$ can be obtained by a simultaneous solution of Eqns. (21 through 25) and Eq. (26) for $t < t_b$ or Eq. (27) for $t > t_b$.

Input to the Model

In order to solve for the upward spread velocity, the model needs various types of inputs:

(a) Physical/derived properties: The group $k\rho c$ and the ignition temperature T_{ig} are obtained from the small scale apparatus LIFT. The heat of combustion is obtained from literature or cone calorimeter apparatus. The ambient temperature should be known.

(b) Flame height correlation constants, K and n: These are obtained from small scale (but turbulent fire) experiments on fully involved vertical samples. Data from a wide variety of materials can be correlated approximately by a single set, K = 0.0433 and n = 0.67 for flame height based on 50% intermittency. For continuous flames, a K value of 0.027 has been found. The correlation is for x_f in meters and $\dot{Q}'$ in kW/m.

(c) Flame heat feedback: At present, $\dot{q}''_w$ is assumed to be constant from x_p to x_f, and then zero, with height. This is approximately true, with a value of 20 to 30 kW/m^2. However, this value can be obtained more accurately for a given material, or a function $\dot{q}''_w(x)$ can be determined from separate experiments and used with a suitable modification of the model.

(d) Local mass Loss Rate: The mass loss rate variation with time must be available for the material. These measurements are discussed in the next section.

Solution: The model was solved using a finite difference method in FORTRAN on a personal computer.

PART C

MEASUREMENT OF LOCAL MASS LOSS RATE

The upward flame spread model needs an input of local mass loss rate per unit area of the fuel as a function of time. The mass loss rate should be determined under similar conditions as the upward flame spread situation. Specifically, the sample must burn in the same orientation (vertical) and uniformly covered with flames, similar to the unburnt material above a pyrolyzing portion of a vertical wall. In order to obtain such data, a small scale test apparatus was designed and fabricated as illustrated in Fig. 2. A 20 cm x 7.5 cm sample is held flush in an inert, surrounding wall. Initially a marinite panel was used for the surrounding wall, however, it was discovered that the panel lost moisture when heated, and absorbed it when cooled down. A moisture loss correction was made to the data already taken, and later, the marinite panel was replaced by an aluminum panel.

The sample was subjected to flames from a natural gas line burner positioned parallel to the lower edge of the sample, well below the sample. Flames from the burner uniformly covered the sample surface, simulating wall material which is covered by flames issued by the downstream, burning surface.

One of the objectives of this project was to systematically study the influence of burnout time, t_b, on the process of upward flame spread. This means samples should be physically thin for a small t_b. However, in order to simulate a typical wall fire, the samples must burn as "thermally thick" solids. (For example, a wall panel will start to burn on the exposed surface, with a heat loss into the interior of the wall, and therefore, the

thin panel will burn like a thermally thick solid.) Hence, thin samples (such as a 1/16" PMMA sheet, a cardboard, a textile material, or a wall panel) were first mounted on a thicker substrate, typically a 1/2" marinite panel, using a glue or a cement or an adhesive. As it was discovered after much testing, the sample preparation was very difficult because the thin sample tended to separate from the substrate during combustion due to high temperature.

The weight of the sample was continuously recorded as m(t). The data were smoothed using a 31-point averaging scheme. From this, the mass loss per unit area, m"(t), was calculated, which was then fitted to a fifth order polynomial;

$$m''(t) = b_5 t^5 + b_4 t^4 + b_3 t^3 + b_2 t^2 + b_1 t + b_o \qquad (28)$$

The mass loss rate per unit area, $\dot{m}''(t)$, is the first derivative of the above expression. Materials tested in this apparatus are, PMMA slabs of 1/16", 1/8", 1/2" and 3/4", polystyrene, polyvinylchloride, textile materials of various types, cardboards of various thicknesses, wall panels, and foam materials. The first set of measurements were made for particle board, which are discussed below.

Mass loss rate for a 0.5" thick particle board was measured in the small scale mass loss rate apparatus. After correcting for the moisture loss, curvefitting, and differentiating, the mass loss rate was found to be:

$$\dot{m}''(t) = 2.95 \times 10^{-15} t^4 - 2.69 \times 10^{-11} t^3 + 4.59 \times 10^{-8} t^2 - 2.82\, t + 1.13 \ \mathrm{kg/m^2.s} \qquad (29)$$

The mass loss rate is plotted in Fig. 3. Using the above curve and other data as input to the model presented earlier, the upward flame

spread velocity and the height of the pyrolysis front are calculated as a function of time, and then compared to existing experimental results. It should be noted that the net mass loss reduced from the data (after taking into account the effects due to moisture loss, thermal expansion of sample-holder, etc.) started from a zero value. However, the first positive value of $\dot{m}''$ was taken as $\dot{m}''(0)$ because the present model has a singularity at $\dot{m}''= 0$. Therefore, the curves in Figures 3, 4, 5 and 6 are extrapolated to zero with a broken line.

Mass loss rates for three other materials, PP-PF (a textile material), 0.030 inch thick clear PMMA, and 1/8" thick Masonite panel are shown in Figures 4, 5 and 6.

PART D

UPWARD FLAME SPREAD: EXPERIMENTAL SETUP

Small Scale Experiments

One of the major objectives of the overall investigation was to simulate wall fires in which a relatively thin wall covering (fuel) is typically mounted on a thicker panel (inertsubstrate), for example, a masonite panel or carpet mounted on a gypsum drywall panel. In order to conduct experiments on such composite walls, we had to first test if the adhesive held during the test runs and how the samples behaved in general. Therefore, some small scale, but turbulent wall fire, experiments were conducted before starting the large scale experiments as described below.

The tests were made on 30 cm x 120 cm samples. Fuel samples were mounted on a 1/2" thick marinite panel using an adhesive, ignited at the bottom using a line burner, and allowed to burn upward. A video recording was made for each test. Tests were carried out on clear and black PMMA sheets 0.030" and 0.060" thick, foam core, cardboards, four different types of nylon and polyester fabrics, Masonite wall panel, and particle board. Six different types of adhesives/cements were tried, namely, Scotch brand adhesive transfer tapes #467 and #9473, Scotch brand spray adhesive #77-N, Omega brand high temperature cement, black furnace cement, and a textile cement. Of these, #9473 tape and furnace cement were found to work reasonably well.

Large Scale Experiments:

In order to verify the model, upward flame spread experiments were conducted on 45 cm x 240 cm samples. Here the overall program objectives were:

(a) to measure $V_p(t)$ and $V_p(x_p)$ for various materials

(b) to measure forward heat flux (ahead of the pyrolysis front) as a function of time and distance

(c) to conduct a systematic study with the burnout time, t_b, as a parameter

(d) to classify materials based on whether they sustain/do not sustain upward propagation (Go/No go tests).

In the past year, most work was conducted on part (a), experimental data were taken on part (b) (which is not yet analyzed fully), and some tests were conducted on part (c). Figure 7 shows a schematic of the setup. Ignition was achieved by a linear gas burner. Heat flux to the wall was measured by five total heat flux gages. Each test run was video-taped and x_f was inferred from the recording. The pyrolysis front was followed visually during the test run, indicated with a pointer, and recorded on the video camera.

PART E

RESULTS AND DISCUSSION

Experimental data and theoretical predictions were obtained for four different materials, (i) 1/2" particle board, (ii) 1/8" Masonite, (iii) 0.030" clear PMMA and (iv) PP-PF (a textile material). These results are presented and discussed in this section.

In plotting the results for pyrolysis and flame tip height, x_p and x_f, against time, predictions were based on a reference time (t=0) as the instant at which the sample started burning, i.e., the inert heating time (t_{inert}) was not included. However, in experiments, the video time clock was started when the igniter was placed at the bottom of the sample and therefore, the recorded time, t, included the inert heating period. It was difficult to note the time at which the samples started burning. Therefore, t_{inert} was estimated from the local mass loss rate experiments. The data for $\dot{m}''(t)$ showed a sudden jump several seconds after the burner was turned on. This time delay was used as t_{inert} as given below.

Sample Type	Time delay, seconds
Particle Board	30
1/8" Masonite	100
0.030" clear PMMA	100
PP-PF	90

The above time period could be estimated only within the accuracy of the time interval between successive data points (3 to 4 sec). Moreover, these values may not correctly represent the actual heating period because they were estimated in the mass loss rate measurement

setup and not in the flame spread apparatus (between which, there was a small difference in detail, like sample size, ignitor location, etc.). However, this inaccuracy is not expected to affect the results significantly because the total burning time is much longer than t_{inert}.

Results are presented in terms of the flame height, x_f, the pyrolysis height, x_p, the energy release rate per unit width, $\dot{Q}'$, and upward flame spread rate, V_p, as a function of time. Also, the maximum pyrolysis height, x_{pmax}, is presented for one material. Of these parameters, the relatively easiest one to measure was the flame height, x_f. The estimation of x_f was obtained as follows. The peak of visible flames (except for an isolated, very small, weak burst of flame spot) in the entire width of the sample, was noted from a frozen video picture. Several (ten to fifteen or sometimes more) readings from the frozen frames within a short inerval (two seconds or less) of time period were read. The two-second time period was much greater than the typical flame tip fluctuation (intermittancy) period. The average of these readings was noted as x_f. The x_f values were determined typically at every 20 to 30 sec. time intervals. Thus, the present value of x_f may be treated as the 50% flame tip intermittency height.

Measurement of x_p was the most difficult. Since the flame covered the wall surface, the pyrolysis front could not be recorded by the camera. Therefore, the pyrolysis front was shown occasionally with a pointer by a person standing next to the burning wall sample and recorded by the camera.

Particle Board:

Predictions for 1/2" thick particle board were made using the following (physical and derived "fire") properties.

$\dot{q}''_w = 25\ kW/m^2$

$k\rho c = 0.93\ (kW/m^2s)^2s$

$h_c = 11.6E03\ kJ/kg$

$T_{ig} = 320\ C$

$T_a = 25\ C$

$t_b = 1380\ s$

$\dot{m}''(t) = 2.95E(-15)t^4 - 2.69E(-11)t^3 + 4.59E(-8)t^2 - 2.82\ t + 1.13(kg/m^2s)$

$K = 0.0433\ m/(kW/m)^{2/3}$

$n = 2/3$

$\dot{Q}'_o = 24.5\ kW/m$

$x_{po} = 0.37\ m$

The predicted maximum pyrolysis height, $x_{p,\ max}$, as a function of the igniter strength is compared with the data of Saito, *et al.*, (1985) in Fig. 8. (This is the only figure here which does not have our data). Comparisons are made for two different values of K (the constant appearing in the flame height correlation). The value of K for 50% flame tip intermittency height has been reported to be 0.0433, and for continuous flame it is reported to be 0.027, with the same exponent of n-2/3 (all units icorresponding to m and kW). Using these two values of K, predictions are found to overestimate and underestimate the data, respectively. At 50% intermittency, the prediction of x_f is "too high" because the heat flux to the wall starts dropping off before $x = x_f$. If x_f is

based on continuous flame (0% intermittentcy), q_w is significant at least up to $x = x_f$. The present model assumes a constant q_w up to $x = x_f$ and then zero thereafter. Therefore, the prediction of $x_{p,\ max}$ is consistent with respect to the K values and the model appears to predict the data well.

Figure 9 shows data and predictions for x_f against time. The solid symbols indicate an average at a given time instant and the bands show the total range of values read for x_f, giving an ideal of typical amplitude of flame tip intermittancy. These bands are dropped from the subsequent figures for clarity. It is seen that the comparison of theory and experiments is reasonable considering that the property data are approximate and that there is a large variation between different batches and samples of the same material.

Other Materials:

Flame height and pyrolysis front data for 1/8" thick Masonite are shown in figures 10, 11 and 12 from two different test runs. The predictions are shown by lines. Data for a 0.030" thick clear PMMA, also obtained from two different test runs, are shown in figures 13 and 14 and compared with predictions. Again, it can be seen that the comparison of data and predictions is good.

Results for a textile material, PP-PF, are shown in Figure 15. This material behaved unusually in the sense that there was a steady vertical propagation of fire with a clearly visible burnout front (x_b) and a steady increase of x_f and x_p, indicating constant values for (x_f-x_b) and (x_p-x_b). Analysis for PP-PF, shown in Fig. 16, clearly failed to predict this upward spread behavior because in this case, the exponent n in the flame height

correlation would be equal to 1.0 and the present analysis does not allow a solution for n = 1.

Some of the other observations we made during the test runs are as follows. Samples often separated from the substrate (which was a 1/2" thick marinite slab); this is probably what happens in actual fires of walls with wall coverings. The width-wise burn pattern was sensitive to air movement surrounding the sample. Since the upward spread rate is much more dominant compared to the lateral spread rate, a sample continues to burn on either left half or the right half if there is asymmetric air movement around the sample. However, this was observed mainly on PP-PF samples where the upward spread rate was slow and the lateral spread was practically nonexistent. If samples are exposed for a relatively short time to the igniter, the fire went out immediately after removing the igniter. If the sample was exposed to the igniter for too long, there was sometimes excessive dripping and/or too much loss of combustibles and again the fire went out. Therefore, achieving a sustained upward spread depended, to some extent, on the ignition sequence.

Figure 17 shows a comparison of the energy release rate per unit width, $\dot{Q}'$, as a function of time for the four materials tested, both from experiments and theory. The "predicted" values of $\dot{Q}'$ were obtained from the "fire property" of local mass loss rate and the predicted upward spread rate, as follows

$$\dot{Q}'(t) = h_c \int_{x_b}^{x_p} \dot{m}''(x)dx$$

$$= \dot{m}''(t)x_{p\infty} + \int_0^t \dot{m}''(t-t')V_p(t')dt' \quad ; t < t_b$$

$$= \int_{t-t_b}^{t} \dot{m}''(t-t')V_p(t')dt' \quad ; t > t_b \tag{30}$$

The values of $\dot{m}''(t)$, t_b, and h_c are available as the properties, x_{po} is a known initial condition, and $V_p(t)$ is available from model prediction.

The experimental value of $\dot{Q}'(t)$ was obtained from the measured values of $x_f(t)$, $x_b(t)$ and the flame height correlation as follows.

$$\dot{Q}'(t) = \left(\frac{x_f - x_b}{K}\right)^{1/n} \tag{31}$$

where K and n are flame height correlation constants, having values of 0.0433 and 0.67, respectively.

Data and predictions of energy release rate per unit width for various materials clearly show the relative fire growth potential for the materials in upward flame spread orientation, which is very common for fires in the initial stage. The PMMA fire is clearly much more hazardous than the textile fires in this situation. Such results have tremendous importance and potential for use in predicting fire growth and for ranking materials in upward flame spreading situations. The predictions appear to adequately represent the experimentally observed performance of materials.

PART F

CONCLUSIONS

The two major achievements of this upward flame spread project (conducted in the last year of the current grant period) are:

(i) We have shown that the behavior of materials *can* be studied individually, and compared relatively on a common basis, in an upward flame spread configuration using well-established experimental procedures, and

(ii) The material performance in the upward flame spread configuration *can* be predicted adequately using a mathematical model for most materials with the input of properly defined and measured "fire properties" of materials.

This is the first attempt to formulate a "complete procedure" for predicting upward flame spread which can be used in a global fire hazard assessment model. Obviously, the model can be modified and refined further for more accurate prediction of upward flame spread for different types of materials, and much more data are needed for a complete validation of this or any other model.

REFERENCES

Ahmad, T. and Faeth, G.M., (1978), An Investigation of the Laminar Overfire Region Along Upright Surfaces. J. Heat Transfer, 100, pp. 112-119.

Ahmad, T. and Faeth, G.M., (1979), "Turbulent Wall Fires," Seventeenth Symposium (International) on Combustion, The Combustion Institute, p. 1149.

Annamalai, K., and Sibulkin, M. (1979a). Flame Spread Over Combustible Surface in Laminar Flow System. I. Excess Fuel and Heat Flux. Combustion Science and Technology, 19, 167-183.

Annamalai, K., and Sibulkin, M. (1979b). Flame Spread Over Combustible Surface in Laminar Flow System. II: Flame Heights and Fire Spread Rates. Combustion Science and Technology 19, 185.

Carrier, G.F., Fendell, F.E. and Fink, S., (1983), "Towards Wind-Aided Flame Spread Along a Horizontal Charring Slab: The Steady-Flow Problem," Combustion Science and Technology, Vol. 32, pp. 161-209.

Chen, C.H., and Tien, J.S., (1983). Fire Plume Along Vertical Surfaces: Effect of Finite-Rate Chemical Reactions. Fire Dynamics and Heat Transfer. HTD-Vol. 25, National Heat Transfer Conference, Seattle, Washington.

deRis, J.N. (1969). Spread of a Laminar Diffusion Flame. Twelfth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 241.

deRis, J.N., (1988). Discussion at the Upward Flame Spread Workshop, FMRC, Boston, MA., unpublished.

Delichatsios, M.A., (1984). Critical Conditions for Sustained Burning and Flame Propagation on Vertical Charring Walls. Factory Mutual Research Technical Report FMRC J.I.OKOj1.BU.

Delichatsios, M.A., (1988). Discussion at the Upward Flame Spread Workshop, FMRC, Boston, MA, unpublished.

Fernandez-Pello, A.C., (1977). Upward Laminar Flame Spread Under the Influence of Externally Applied Thermal Radiation. Combustion Science and Technology, 17, 87.

Fernandez-Pello, A.C., (1978). A Theoretical Model for the Upward Laminar Spread of Flames Over Vertical Fuel Surfaces. Combustion and Flame, 31, 135.

Fernandez-Pello, A.C. (1979). Flame Spread in a Forward Forced Flow. Combustion and Flame, 36, 63.

Fernandez-Pello, A.C., and Mao, C.P., (1981). A Unified Analysis of Concurrent Modes of Flame Spread. Combustion Science and Technology, 26, 147.

Fernandez-Pello, A.C. and Quintiere, J.Q., (1982). A Simplified Model of Radiating-Turbulent-Upward Flame Spread Over the Surface of a Charring Combustible, Eastern Section of the Combustion Institute, Fall 1982 Technical Meeting.

Fernandez-Pello, A.C. and Hirano, T., (1983). Controlling Mechanisms of Flame Spread. Combustion Science and Technology, 32, pp. 1-31.

Frey, A.E., Jr., and Tien, J.S., (1979). A Theory of Flame Spread Over a Solid Fuel Including Finite Rate Chemical Kinetics. Combustion and Flame, 36, 263.

Glassman, I., (1978). Some Perceptions on Condensed Phase Flame Spreading and Mass Burning. J. Fire and Flammability, 9, 88.

Hansen, A., and Sibulkin, M., (1974). Flame Spreading from a Point Source of Ignition on a Vertical Fuel Surface. Combustion Science and Technology, 9, 173.

Harkleroad, M., Quintiere, J., and Walton, W., (1983). Radiative Ignition and Opposed Flow Flame Spread Measurements on Materials. U.S. Dept. Trans., Fed. Aviation Admin. Tech. Ctr., DOT/FAA/CT-83/28.

Harkleroad, M. and Tu, K.M., (1988). Private communication.

Hasemi, Y., (1984). Experimental Wall Flame Heat Transfer Correlations for the Analysis of Upward Flame Spread. Fire Science and Technology, 4, No. 2, 75-90.

Hasemi, Y., (1986). Thermal Modeling of Upward Wall Flame Spread. Fire Safety Science, Proceeding of the First International Symposium, Hemisphere Pub. Corp., p. 87.

Janssens, M., (1988). Private communication.

Kinoshita, C.M., and Pagni, P.J., (1981). Stagnation-point Combustion with Radiation. Eighteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA. (in press).

Kulkarni, A.K. (1987). Radiative Heat Transfer from Wall Flames. Radiation, Phase Change Heat Transfer, and Thermal Systems, HTD-Vol. 81, Ed. Jaluria *et al.*, proceedings of ASME Winter Annual Meeting, Boston, MA, p. 9.

Lawson, D.I., Webster, C.T. Gregsten, M.J., (1955). The Flammability of Fabrics. J. Text. Inst., 46 (7) T 453-63.

Luikor, A.V., (1968). Analytical heat Diffusion Theory, Academic Press, p. 2, 172.

Markstein,G.H., and deRis, J., (1972). Upward Fire Spread Over Textiles. Fourteenth Symposium (International) on Combustion. The Combustion Institute, Pittsburgh, PA, p. 1085.

Mitler, H.E., (1986). 1986 Annual Fire Research Conference, National Bureau of Standards, Gaithersburg, MD.

Mitler, H.E., (1988). Discussion at the Upward Flame Spread Workshop, FMRC, Boston, MA, unpublished.

Orloff, L., deRis. J., and Markstein,G.M, (1975). Upward Turbulent Fire Spread and Burning of Fuel Surfaces. Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 1329.

Quintiere, J.G., (1981). A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus. Fire and Materials, 5, 2, p. 56.

Quintiere, J., Harkleroad, M., and Walton, D., (1983). Measurement of Material Flame Spread Properties, Combustion Science and Technology, 32, p. 67.

Quintiere, J., (1985b). Some Factors Influencing the Fire Spread Over Room Linings and in the ASTM E 84 Tunnel Test. Fire and Materials, 9, No. 2, p. 65.

Quintiere, J., (1985a). Unpublished notes, private communication.

Quintiere, J.G., Harkleroad, M. and Hasemi, Y., (1986). Wall Flames and Implications for Upward Flame Spread. Combustion Science and Technology, 48, pp. 191-222.

Quintiere, J.G., (1988). The Application of Flame Spread Theory to Predict Material Performance. J. Res. of the National Bureau of Standards, 93, pp. 61-70.

Sibulkin, M., and Kim, J., (1977). The Dependence of Flame Propagation Rates on Surface Heat Transfer. II: Upward Burning. Combustion Science and Technology, 17, p. 39.

Saito, K., Williams, F.A., and Quintiere, J.G., (1986). Upward Turbulent Flame Spread, Fire Safety Science, Proceedings of the First International Symposium, Hemisphere Pub. Co., p. 75-86.

Saito, K., Williams, F.A., Wichman, I.S. and Quintiere, J.G., (1987). Upward Turbulent Flame Spread on Wood Under External Radiation. National Heat Transfer Conference, paper no. 87-HT-86, Pittsburgh, PA, August 9-12, 1987.

Thomas, P.H., and Lawson, D.I., (1957). On the Minimum Speed of Flame Propagation in Fabrics. Joint Fire Research Organization. Fire Research Note 288, Borehamwood, U.K.

Thomas, P.H., and Webster, C.T., (1960). Some Experiments on the Burning of Fabrics and the Heights of Buoyant Diffusion Flames. Joint Fire Research Organization. Fire Research Note 420, Borehamwood, U.K.

Thomas, P.H., (1975). Some Physical Aspects of the Spread of Fire. FoU-brand 1, p. 1.

Wichman, I.S. and Baum, H.R. (1988) and others. An Integral Analysis of Two Simple Model Problems of Wind Aided Flame Spread (in press).

Williams, F.A., (1976). Mechanisms of Fire Spread. Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 1281.

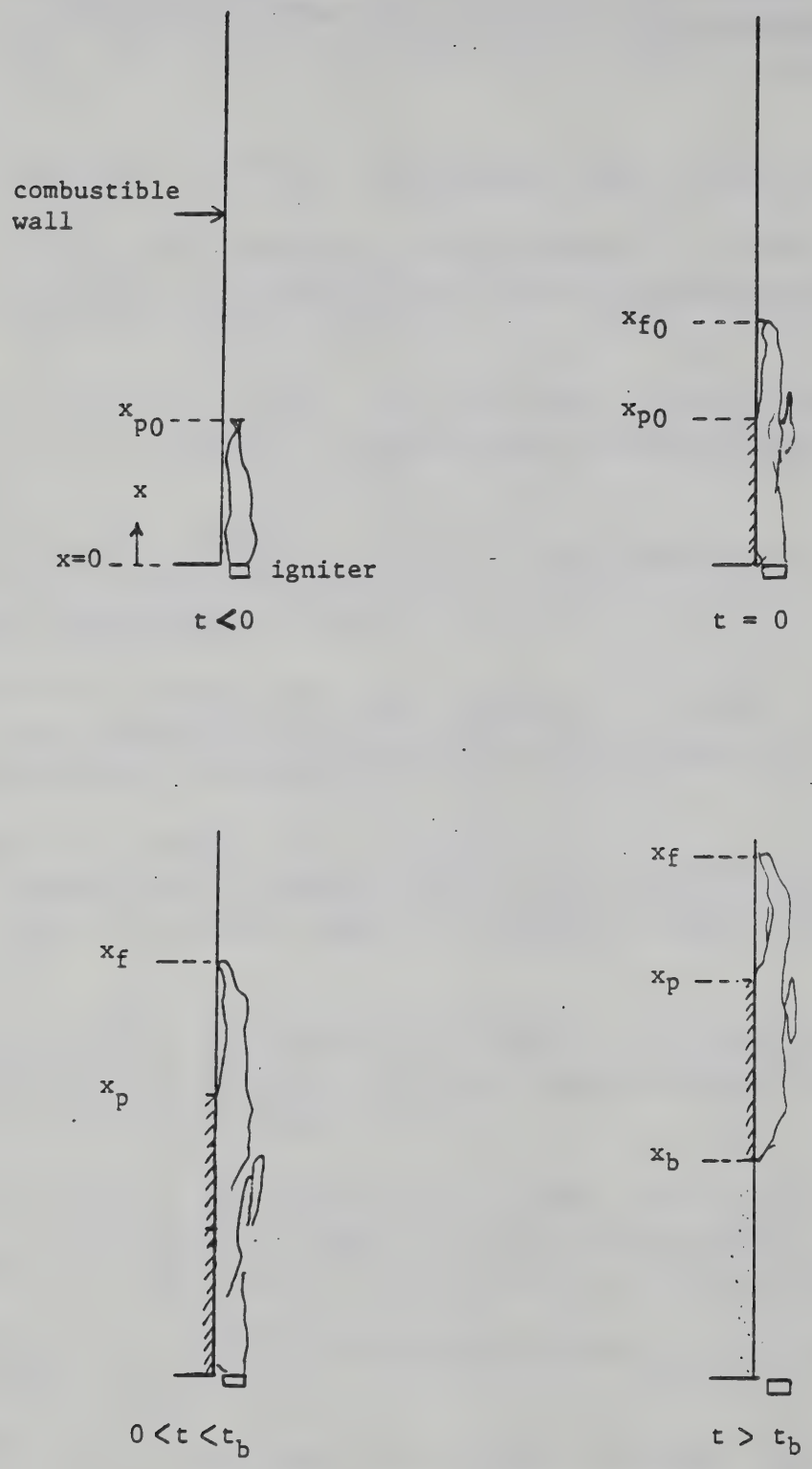

Fig. 1 : A physical model of upward flame spread on a vertical wall.

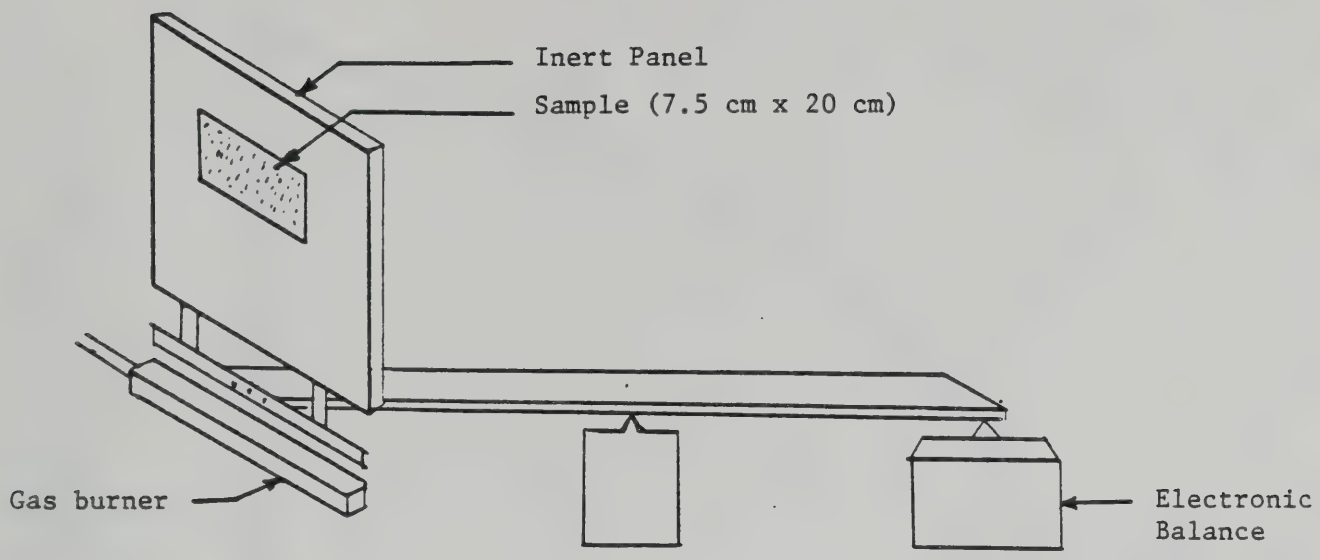

Figure 2 : A schematic of mass loss rate experimental setup

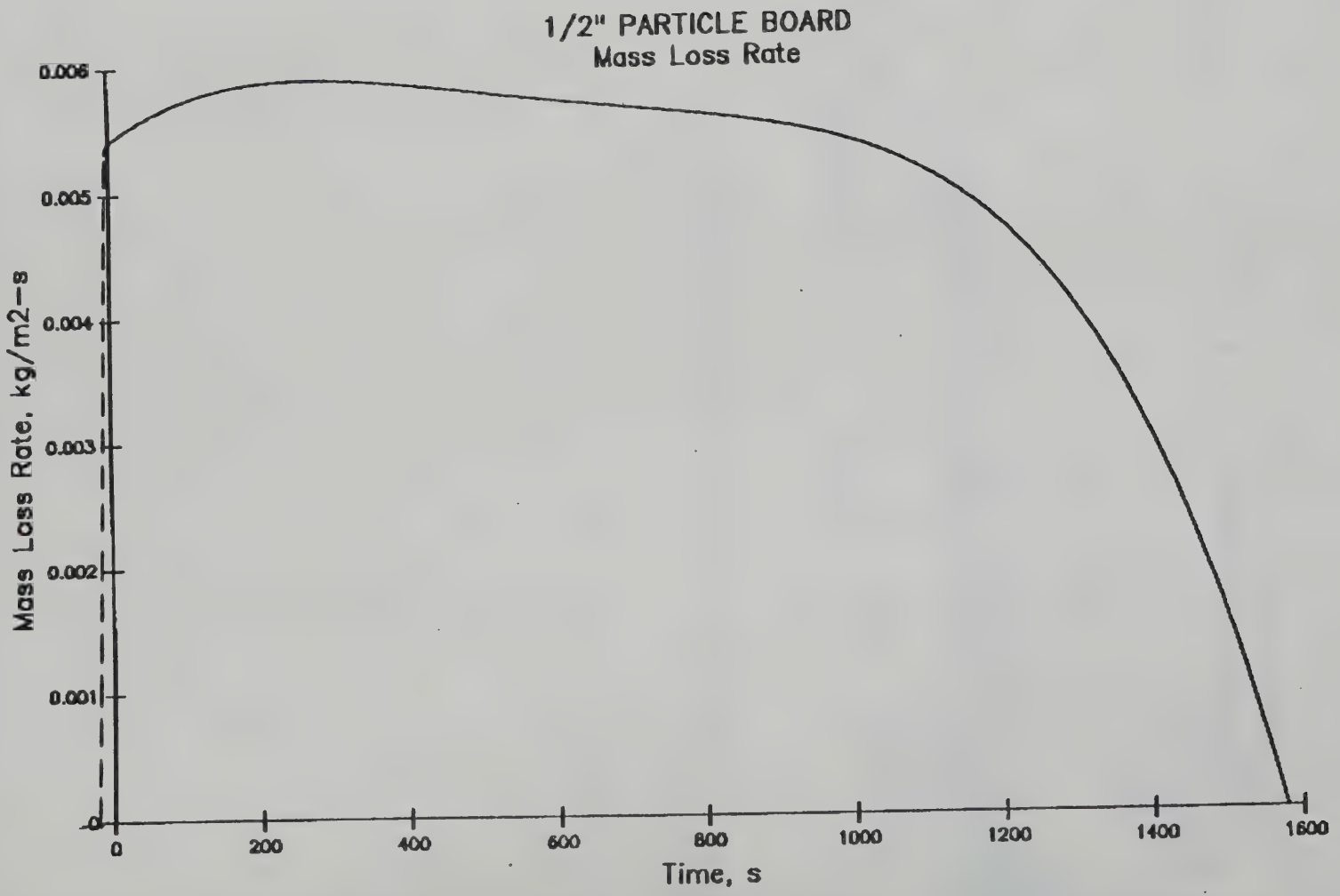

Figure 3: Local mass loss rate as a function of time for ½" Particle Board. The broken line indicates that the actual $\dot{m}''$ should begin at zero; however, for the convenience of using the model (which has a singularity at $\dot{m}''=o$), the $\dot{m}''(t)$ is started at the first nonzero value obtained in the experiments. Please refer to the text for more explanation.

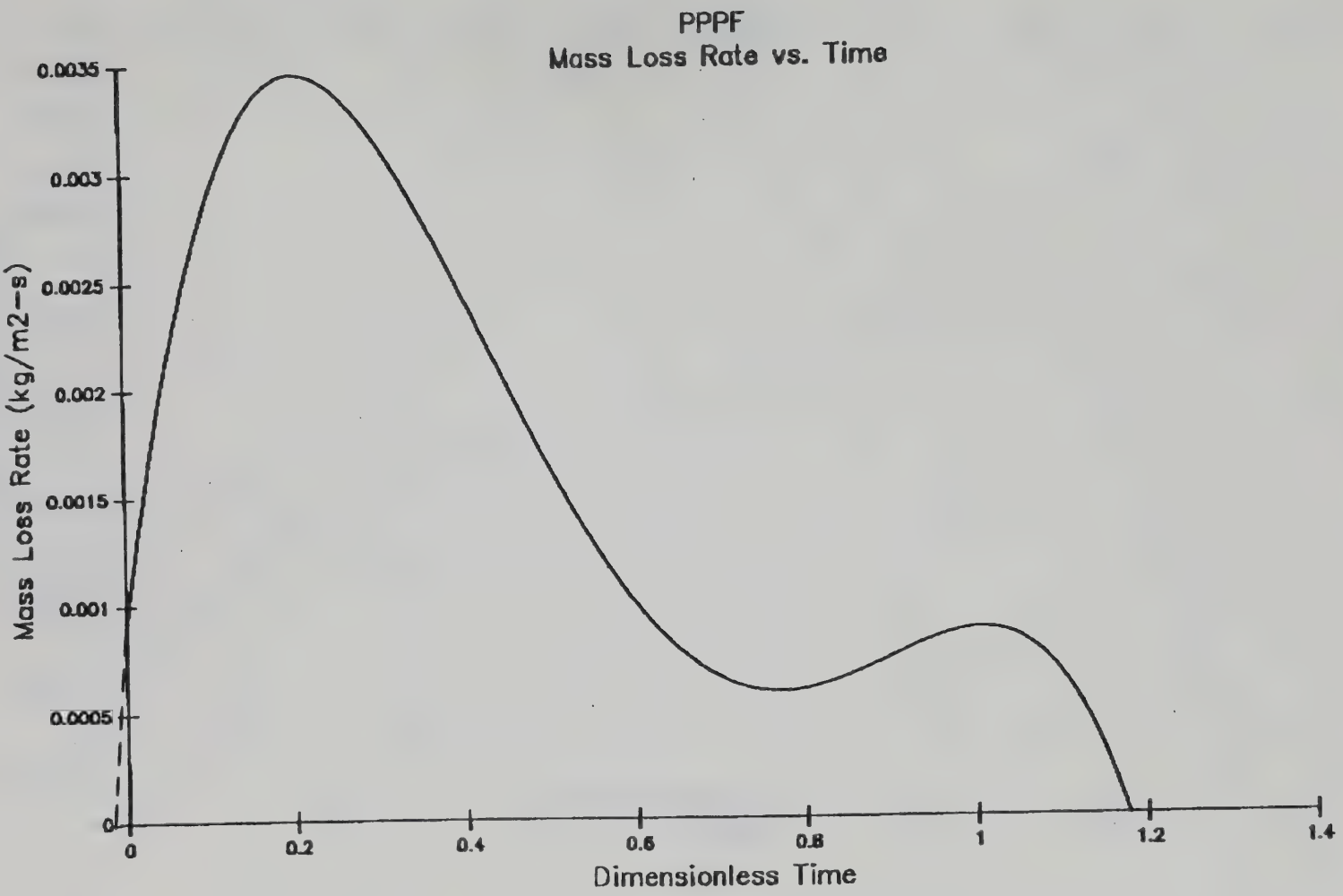

Figure 4: Local mass loss rate as a function of time for PP-PF.

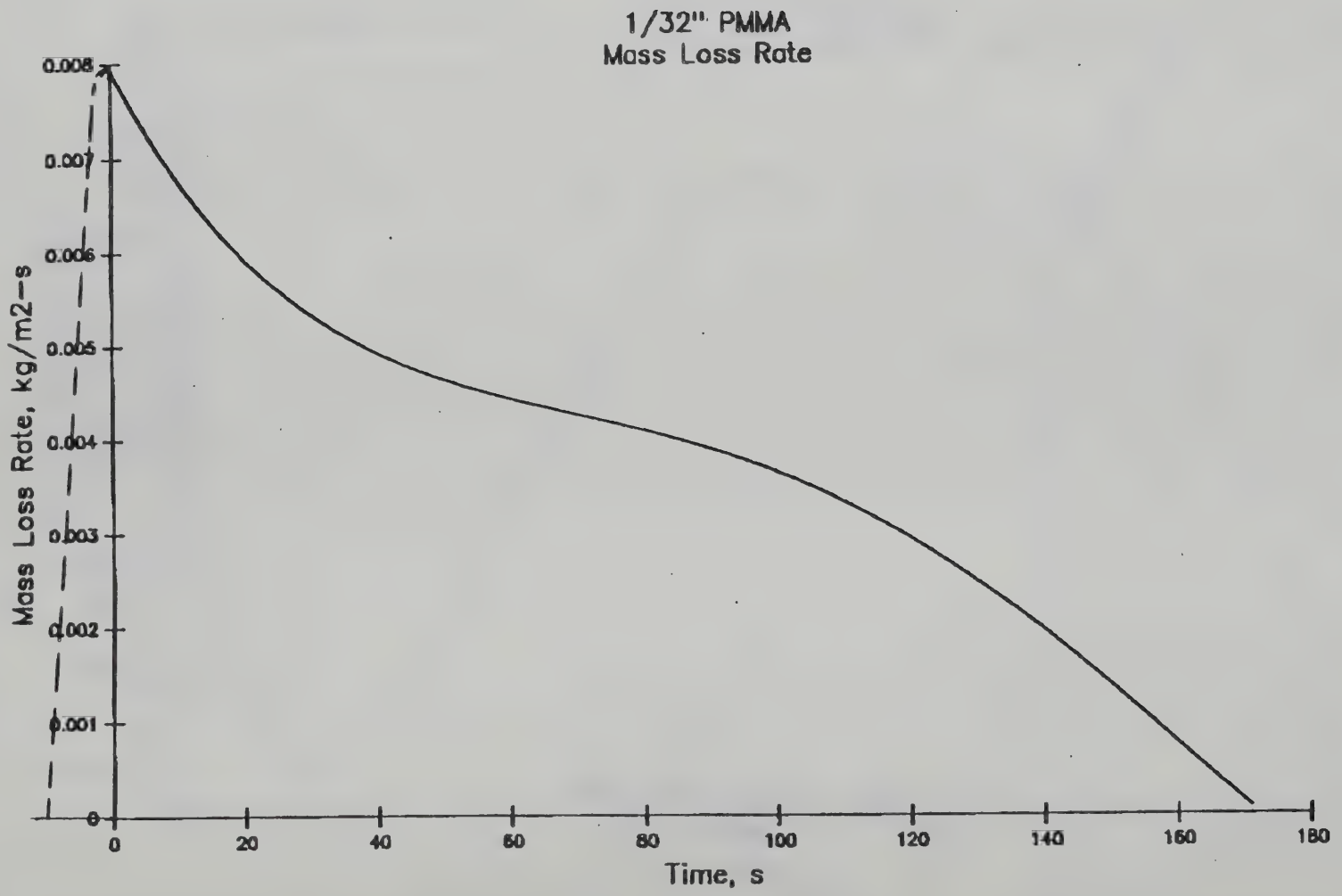

Figure 5: Local mass loss rate as a function of time for 0.030" clear PMMA.

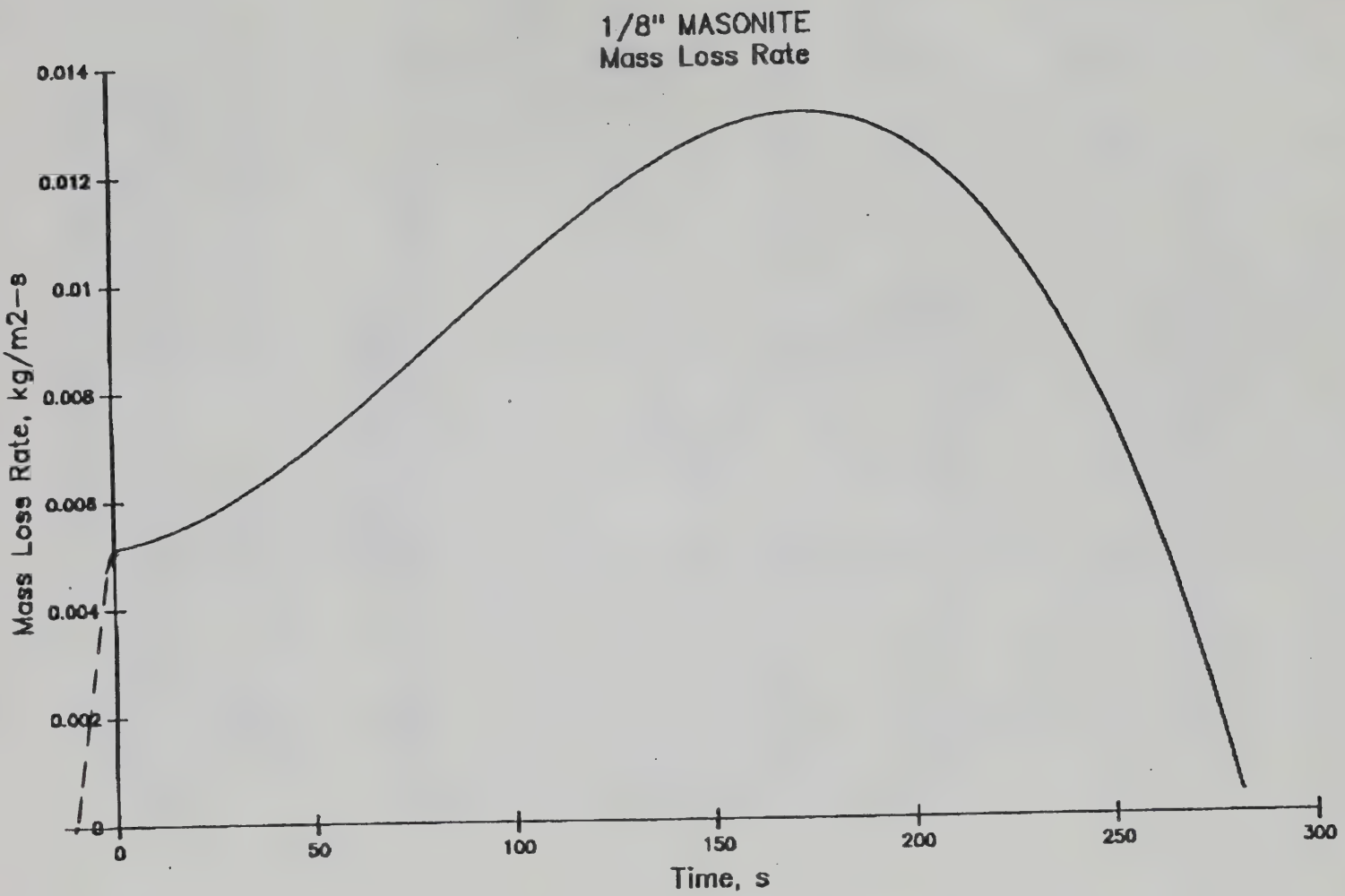

Figure 6: Local mass loss rate as a function of time for 1/8" masonite board.

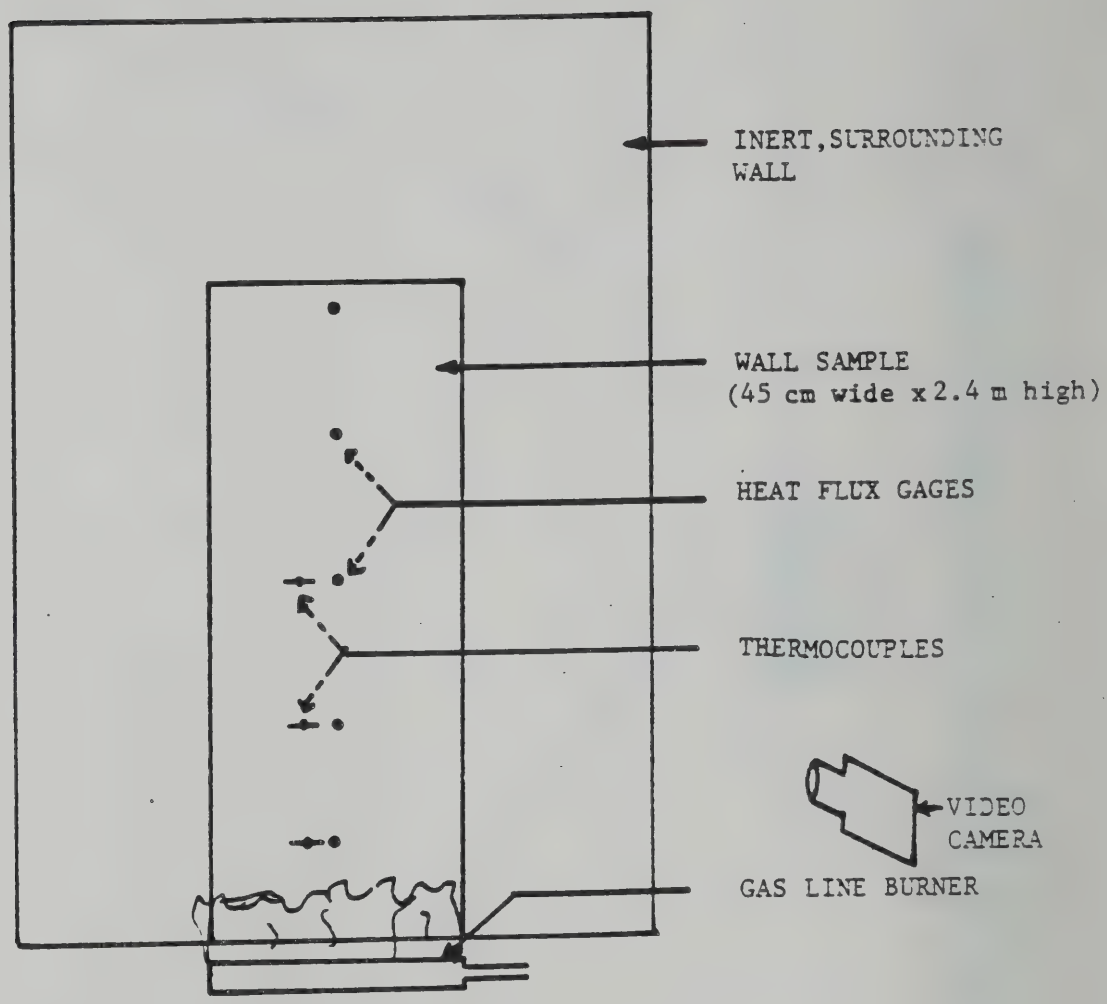

Figure 7 : Apparatus for upward spread experiments

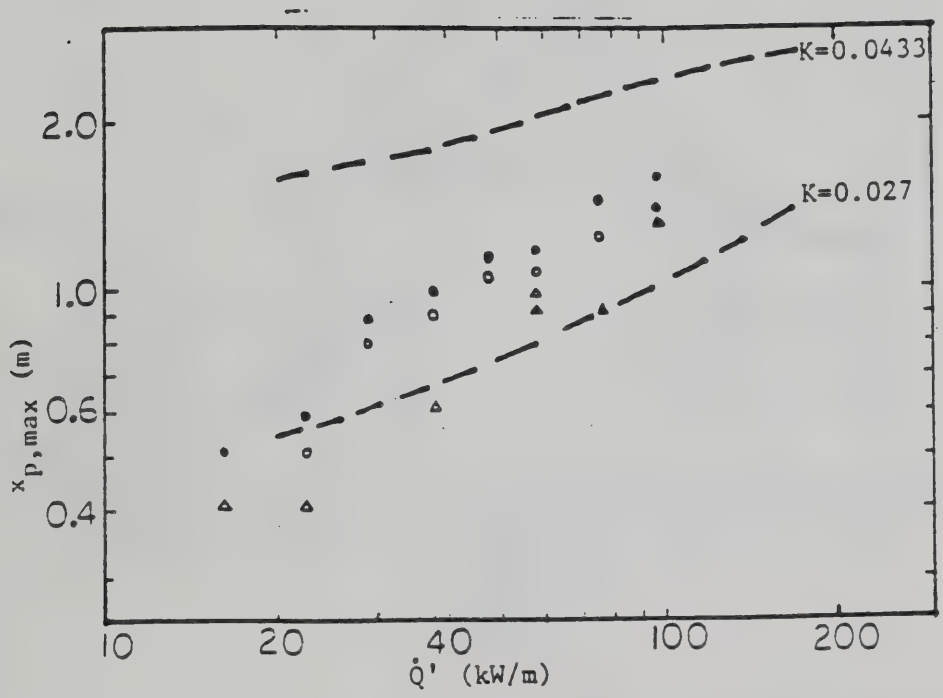

Figure 8: Pyrolysis front height at extinction as a function of burner energy supply rate for particle board. Symbols are data of Saito et al. (1985) for three different definitions of pyrolysis front; dashed lines are predictions using present model.

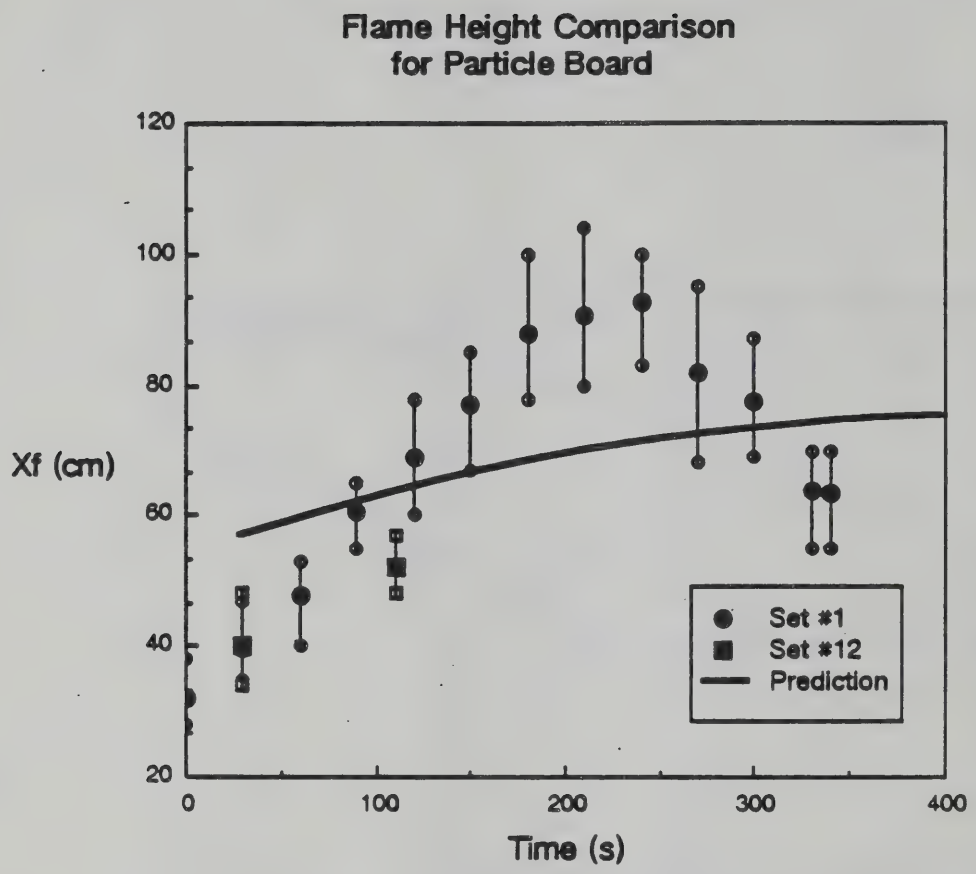

Figure 9: Measured and predicted values of flame tip height for ½" Particle Board.

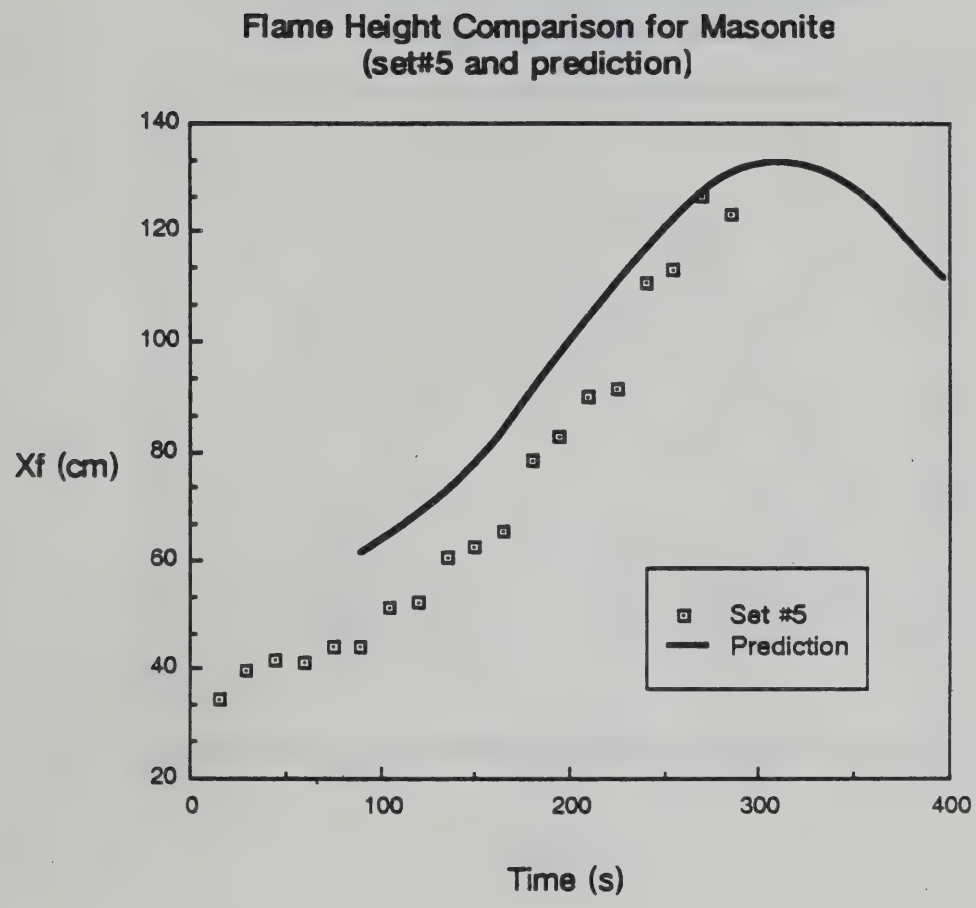

Figure 10: Measured and predicted values of flame tip height for 1/8" Masonite Board.

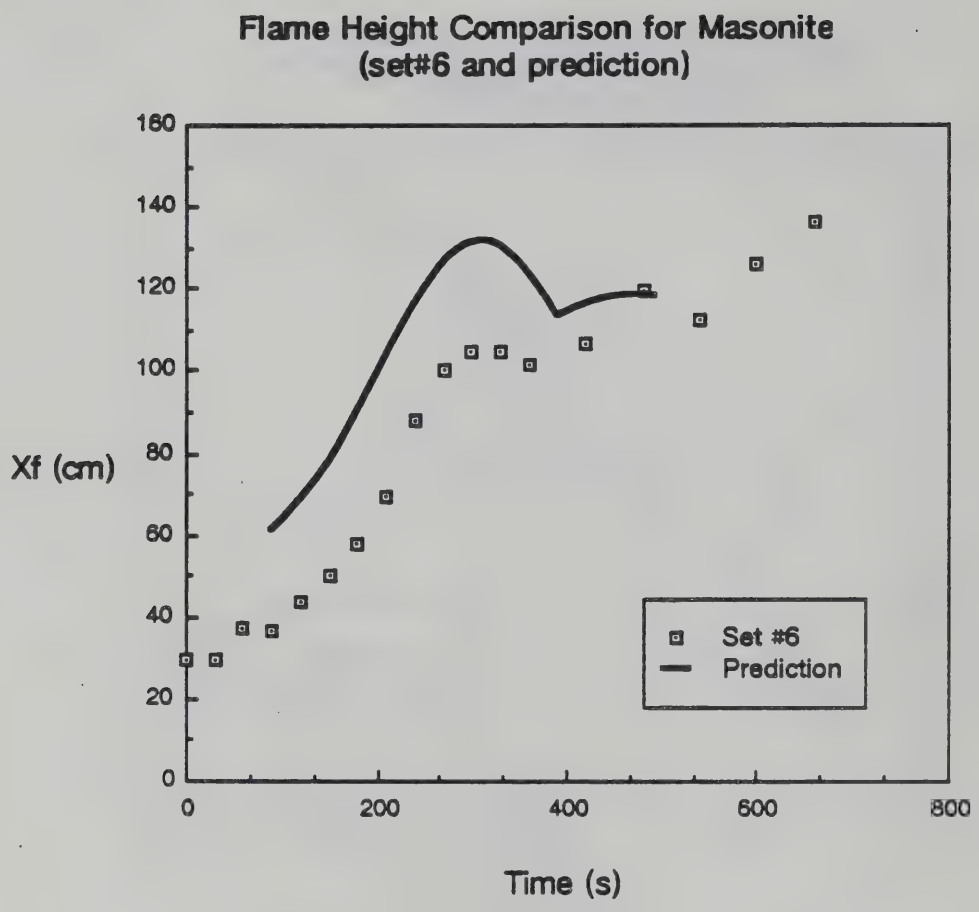

Figure 11: Measured and predicted values of flame tip height for 1/8" Masonite Board.

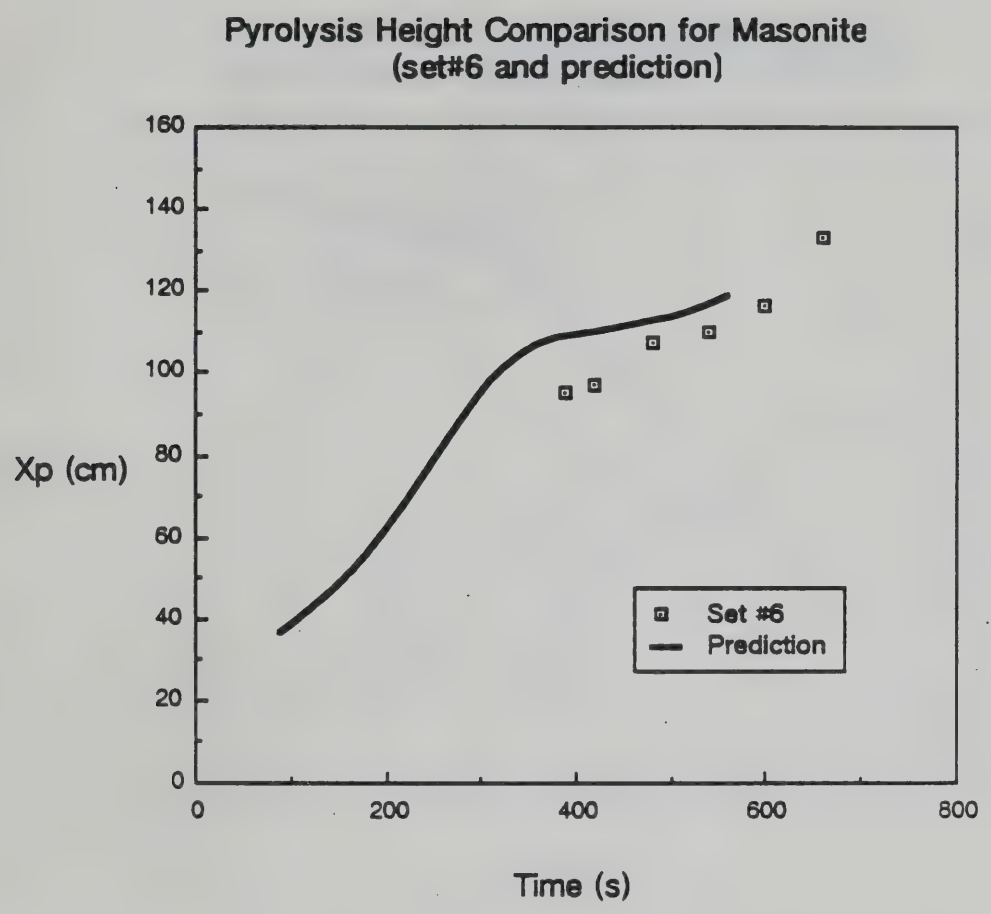

Figure 12: Measured and predicted values of pyrolysis height for 1/8" Masonite Board.

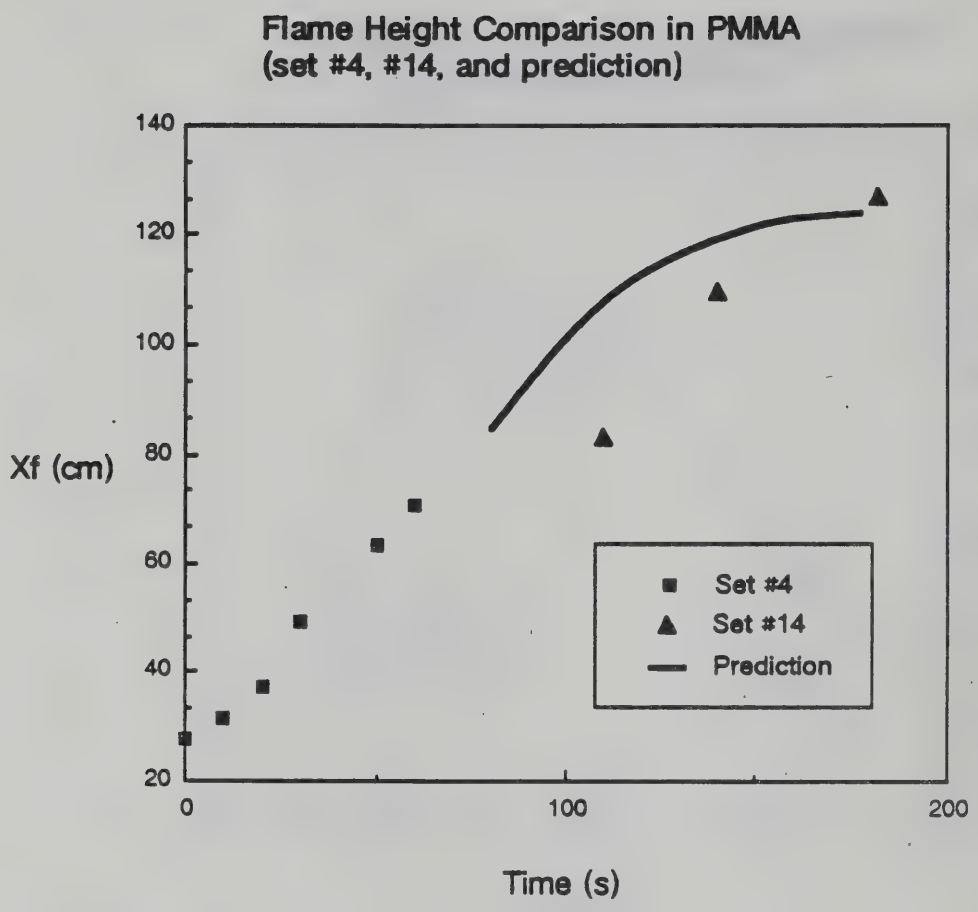

Figure 13: Measured and predicted values of flame tip height for 0.030" clear PMMA sheets.

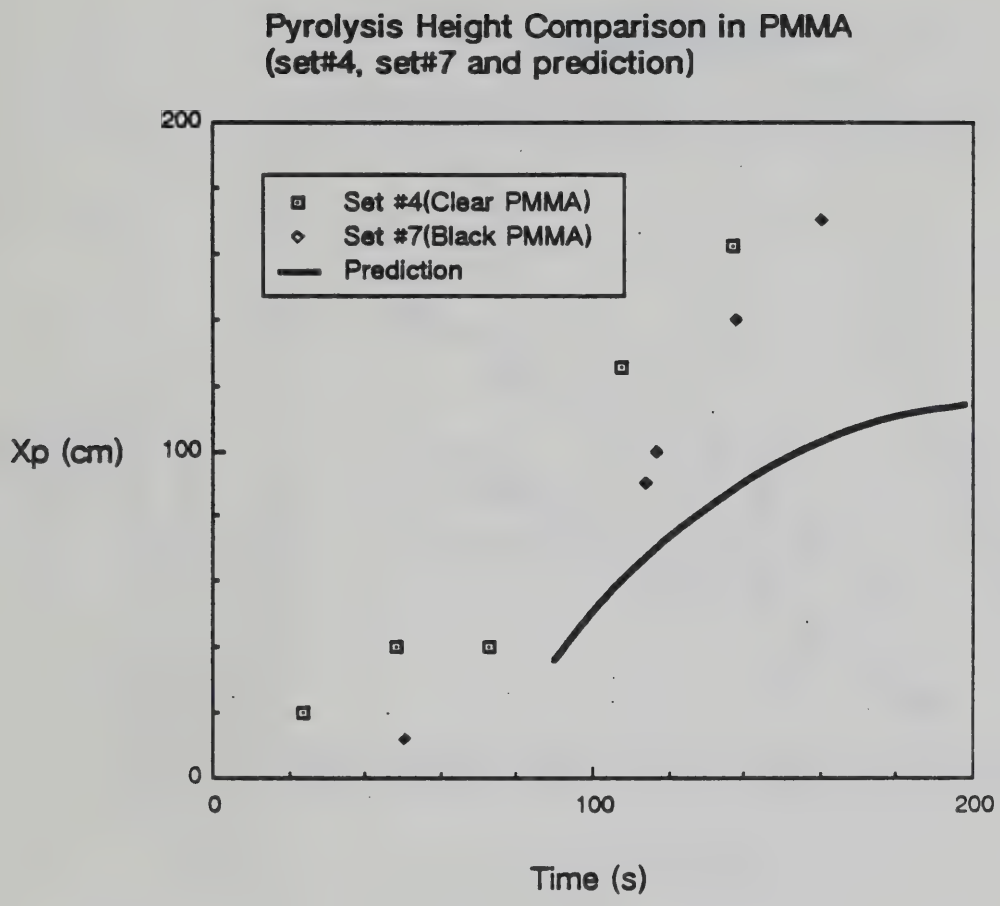

Figure 14: Measured and predicted values of pyrolysis height for 0.030" clear and black PMMA sheets.

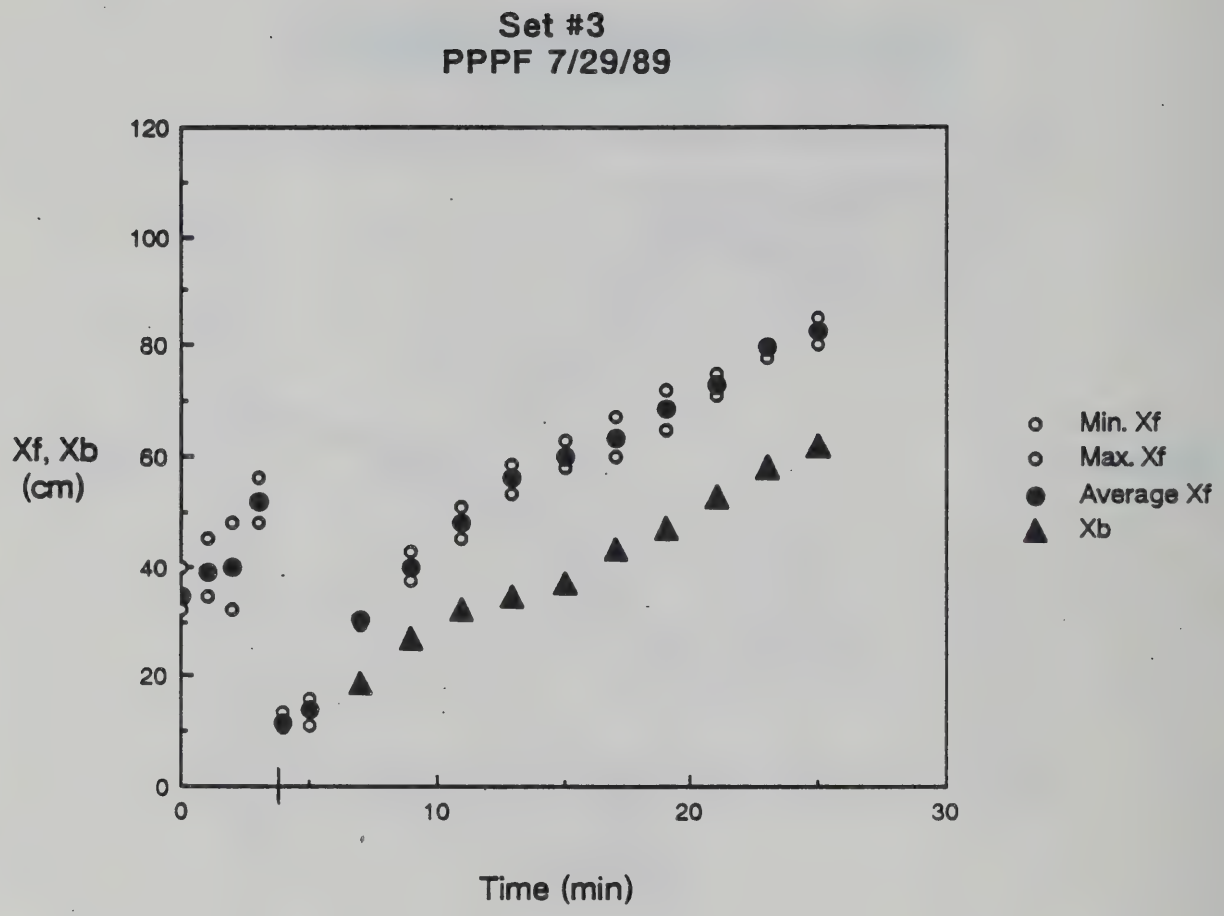

Figure 15: Measured values of flame tip height and burnant edge height for P P-P F

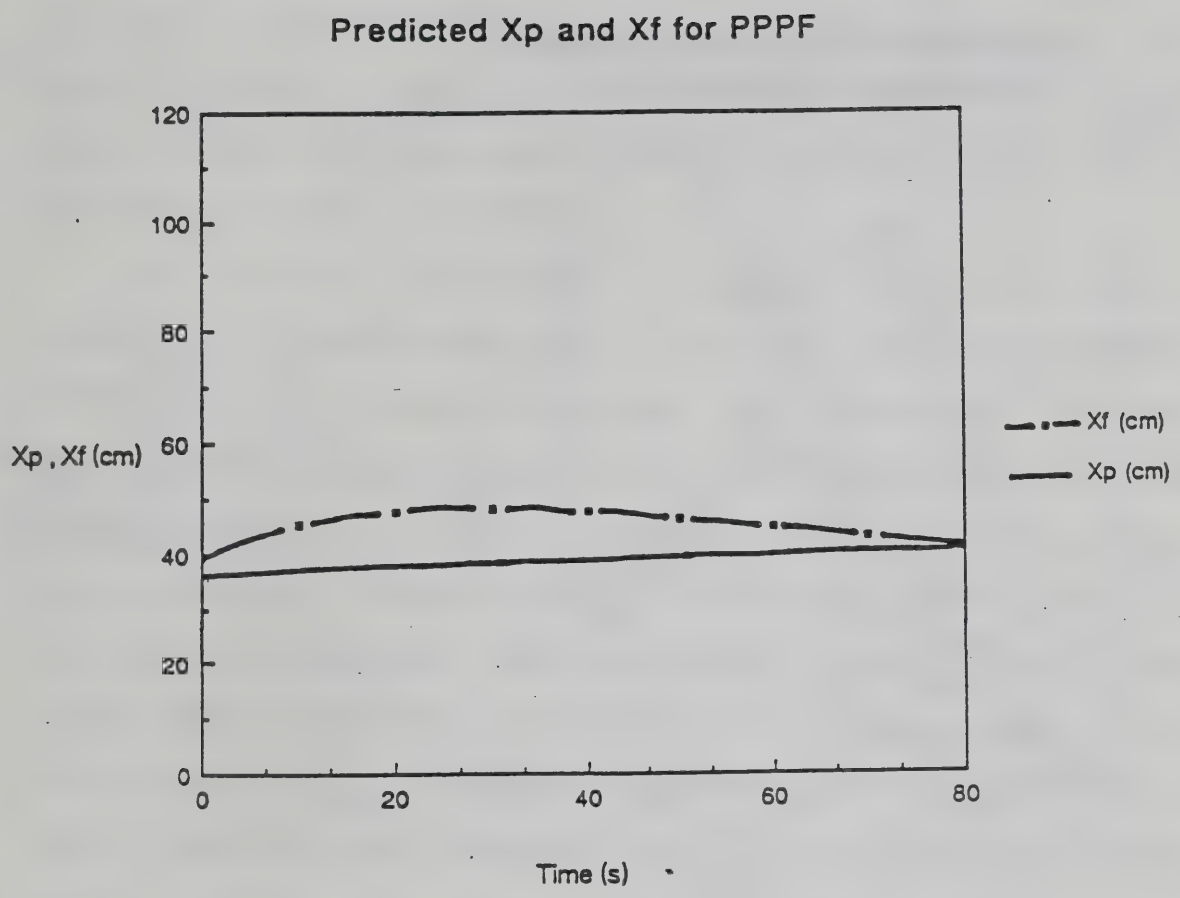

Figure 16: Predictions for pyrolysis height and flame tip height for PP-PF.

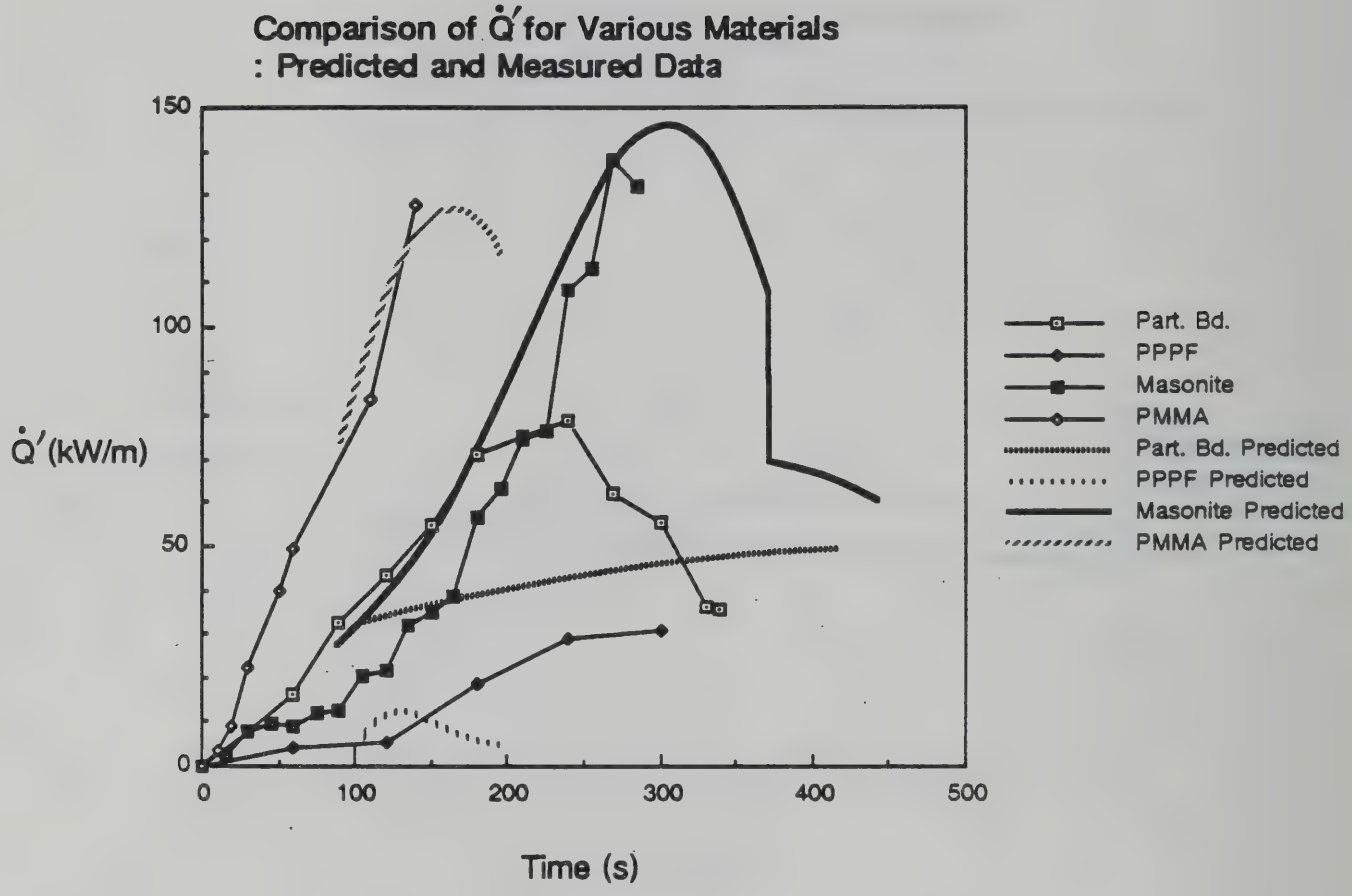

Figure 17: Measured and predicted values of energy release rate for various materials as a function of time.

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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Progress made on NIST Grant No. 60NANB4D0037 is reported here. Since the three previous annual reports describe the work conducted in the first three years, the scope of this report is limited to the past (and final) year of the grant, in which a study of upward flame spread on vertical walls was conducted. First, a detailed review of literature on upward flame spread is presented. A "complete procedure" for predicting upward flame spread on practical materials, which can be used in a global fire hazard assessment model, is then described. Experimental results on upward flame spread on various materials are obtained and the validity of the model is established.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

flame spread; hazard assessment; masonite (trademark); particle boards; polymethylmethacrylate

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